JEGEL 86018

October 1986

MANITOBA SLAGS
DEPOSITS, CHARACTERIZATION, MODIFICATIONS
POTENTIAL UTILIZATION
APPENDICES

23440-5-9250/01-SQ

Prepared For:

MINERAL SCIENCES LABORATORY
CANADA CENTRE FOR MINERAL AND ENERGY TECHNOLOGY

By:

JOHN EMERY GEOTECHNICAL ENGINEERING LIMITED
16 Four Seasons Place, Suite 107
Etobicoke, Ontario M9B 6E7
416-621-2305

216pp

MICROMEDIA

Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources Canada, funded as part of the Canada/Manitoba Mineral Development Agreement.

APPENDIX A

KEY NONFERROUS SLAG REFERENCES UP TO 1980

A1 to A4 — BRE, "Utilization of Industrial By-Products and Waste Materials", Library Bibliography 255, Building Research Establishment, Garston, England, June 1975. [17]
Chapter 8.2 - Metallurgical Slags.

A5 to A12 — Nurse, R.W., "Use of Slag in Cement Production: Notes on a Visit to Japan and Australia", IC 41/69, Building Research Station, Garston, England, July 1969. [43]

A13 to A16 — Chalyi, L.V., Kravchenko, V.T. and Shternbek, E.O., "The Use of Nickel Slags for Making Stowing Mixtures", (Translated from the Russian, Gran. Zh, 1974, 150(2)), Library Translation No. 1917, Building Research Establishment, Garston, England, May 1975. [27]

A17 to A22 — OECD, Use of Waste Materials and By-products in Road Construction, Organization for Economic Co-operation and Development, Paris, 1977. [18]
Chapter 9 - Non-Ferrous Slags (Prepared by J.J. Emery).

A23 — Zhi-yuan, C., "The Activity of High Magnesia Nickel Slag", Abstract, International Conference on the Use of By-products and Waste in Civil Engineering, Paris, November 1978. [44]

A24 to A26 — Gutt, W. and Nixon, P.J., "Use of Waste Materials in the Construction Industry - Analysis of the Rilem Symposium by Correspondence", Matériaux et Constructions, Vol. 12, No. 70, 1979. [20]
Chapter 3 - Other Metallurgical Slags.

8.2 : METALLURGICAL SLAGS

379. Limestone-slag cement based on slags from the copper-nickel industry:
GUDOVICH, L.A. and TIMOSHENKO, O.M.:
Met. Shlaki Monchi i Pechengi. Akad. Nauk SSSR. Kol'sk Filial, 1965, 80-124; (in Russian); Chem. Abs., 1965, 63, 8016b.
The slags contain 39-42% SiO_2 and 32-35% FeO. Limestone, slag, and up to 7% gypsum are mixed to make a cement mix.

380. Phase composition and structure of slags obtained during the production of yellow phosphorus:
VLADIMIROVA, L.A.:
Stroit. Mater. Izdeliya Met. Shlakov. Ural. Nauch. - Issled. Proekt. Inst. Stroit. Mater., 1965, 286-93; (in Russian); Chem. Abs., 1967, 66, 47850e.
Presents the results of petrographic and x-ray analysis of slags obtained during production of phosphorus in an electric furnace.

381. Effect of changes in chemical compositions of slags from copper smelting on the mechanical properties of cast slag products:
BRAGIN, B.A. and NAGORNYI, A.I.:
Tr. Alma-At. Nauch. - Issled. Proekt. Inst. Stroit. Mater., 1966, (7), 19-21; (in Russian); Chem. Abs., 1968, 68, 32916y.
The composition of slags from two copper plants are considered in relation to their mechanical properties and acid resistance.

382. Phosphorus slags for the production of hydrothermally hardening binders:
FUNTIKOV, V.I., KOLBASOV, V.M. and KUZNETSOVA, M.N.:
Tr. Mosk. Khim. - Tekhnol. Inst., 1966, (50), 140-3; (in Russian).
Phosphorus slag mixed with lime or Portland cement and treated hydrothermally gives a strong rock-like material. Granulation of the slag considerably increases its activity.

383. Study of hardening of binders from nonferrous metal slags:
VOLZHENSKII, A.V., VINOGRADOV, B.N. and KHARINA, T.V.:
Izv. Vyssh. Ucheb. Zaved., Stroit. Arkhitekt., 1966, 9(8), 75-80; (in Russian); Chem. Abs., 1967, 66, 79281m.
The autoclave hardening and steam hardening of nickel, copper, and polymetallic slags was studied.

384. Kara-Tau electrothermal phosphorus slags:
KUATBAEV, K.K.:
Stroitelnye Materialy, 1968, 14(ii), 32-33; (in Russian).
The Alma-Ata symposium papers on the possible uses of slags in the building industry are reviewed.

385. Use of by-products, obtained during the production of metallurgical dolomite, for production of building materials:
LISOVAYA, E.D., LIVSON, Z.A., KOZLOVA, E.I., et al:
Khim. Tekhnol., 1968, (10), 63-68; (in Russian); Chem. Abs., 1969, 71, 15758t.
The possibilities of using caustic dust and fired dolomite as additives in Portland cement clinker were studied.

386. Phosphorus slags in the production of cement:
STEPANOV, V.M.:
Tsement, 1968, 34(5), 17; (in Russian); Chem. Abs., 1969, 70, 50195h.
Describes the production of cements in which granulated phosphorus slags are used in place of blastfurnace slag. Properties of the slags and cements are discussed.

387. Heavy oil well cement from a lead slag:
BASH, S.M.:
Tsement, 1969, (1), 12-13; (in Russian); Chem. Abs., 1969, 71, 84272s.
The slag left after reducing sulphide ores contains up to 90% of a glassy phase and is 10% crystalline. Its composition is given. The ratio CaO/SiO_2 = 0.57. Because of the large quantities available the possibility of using it as a heavy cement for oil wells was investigated; the hydraulic activity, however, was very low. Means of improving this are described.

388. Binders from wastes of asbestos-cement and electrophosphorus production:
BASHEV, F.P.:
Tsement, 1969, (4), 8-9; (in Russian); Chem. Abs., 1969, 71, 33126q.
The effect of air and water hardening on mixtures of asbestos-cement waste and electrophosphorus slag was investigated. It was shown that the optimum mix contains 10-15% asbestos-cement; the water/solid ratio has a significant effect on strength.

389. Effect of phosphorus slags on the atmospheric resistance of Portland cement:
KANTSEPOL'SKII, I.S. and TEREKHOVICH, S.V.:
Tr. Alma-At. Nauch. - Issled. Proekt. Inst. Stroit. Mater., 1970, (12), 205-11; (in Russian); Chem. Abs., 1973, 78, 47274.

390. Physicochemical properties of slags from the Novolipetsk metallurgical plant as raw material for the production of building materials:
VASIL'EVA, G.M., ALEKSANDROV, S.E. and GORSHKOV, V.S.:
Sb. Tr., Vses. Nauch. - Issled. Inst. Nov. Stroit. Mater., 1970, (26), 99-106; (in Russian); Chem. Abs., 1973, 78, 47315g.
Wide variations in the chemical composition of the slags were found; the dominant phase is Beta-C_2S. Compressive strengths of specimens made from them also show considerable variation.

391. Sulphate-resistant slag Portland cement based on phosphoric slags:
KLASSEN, A.N. and TEREKHOVICH, S.V.:
Khim. Khim. Tekhnol. (Alma-Ata), 1971, (12), 128-32; (in Russian); Chem. Abs., 1973, 78, 114789.

392. Sulphate-resistant phosphoric slag cement:
BASHEV, F.P.:
Tr., Vses. Nauch. - Issled. Inst. Tsem. Mashinostr., 1972, (13), 98-102; (in Russian); Chem. Abs., 1973, 79, 128827.

393. Slag Portland cement from granulated magnesia-iron slags from copper-nickel plants:
GUREVICH, B.J. and GUDOVICH, L.A.:
Prir. Tekhnogennoe Syr'e Kol'sk. Poluostrova, 1972, 80-102; (in Russian); Chem. Abs., 1973, 79, 57171.

394. Raw mixes [for cement] with additions of copper slag:
ROYAK, S.M., KITSIS, S.B. and ZHOVTAYA, V.N.:
Tsement, 1972, (4), 12-13; (in Russian).
Reports on the beneficial mineralizing effect of 3-6% of slag from copper extraction in the production of cement clinker. The slag contains about 40% of ferrous oxide, plus calcium and magnesium oxides.

395. Cementless aerated slag concrete made from titanium slag:
ROZENFEL'D, L.M., VASIL'EVA, T.D. and DEM'YANOV, V.A.:
Vop. Tekhnol. Yacheistykh Betonov Konstr. Nikh, 1972, 94-101; (in Russian); Chem. Abs., 1973, 79, 23038.

396. Experimental manufacture of reinforced panels from lightweight autoclave cement with artificial aggregates:
STAMENOV, ST., VACHEV, D. and KHARIZANOVA, L.:
Stroitelstvo, 1972, 19(9), 17-19; (in Bulgarian); Chem. Abs., 1973, 78, 163382.
Satisfactory concrete was prepared in which the cement was completely replaced by metallurgical slags.

397. Mineralizing action of phosphorus slag during the roasting of high-alkali raw material:
BUTT, YU.M., IMASHEV, M.K. and GREBNEVA, V.P.:
Tsement, 1973, (1), 17-18; (in Russian); Chem. Abs., 1973, 78, 139693.

398. Use of zinc smelter waste as highway construction material:
HUGHES, M.L. and HALIBURTON, T.A.:
Highway Research Record, 1973, (430), 16-25.
Four types of Oklahoma zinc smelter waste were studied as aggregates in asphalt mixes, and as stabilized base, and were found to be suitable in particular phases of highway construction. Natural gradation can be modified by addition of very fine natural sand ('blow sand') for asphalt mixes. Smelter wastes should increase skid resistance of mixes based on limestone aggregate; they cannot be used in Portland cement concrete because of cement/aggregate reaction.

399. The use of a pseudowollastonite slag for ceramic purposes:
NEL, P.J.:
South African C.S.I.R., National Building Res. Inst., Special Report BOU 31, Pretoria, 1973, 5pp.
The Mineralogical and chemical compositions of air-cooled slag from a phosphate plant were studied, and its firing and glazing properties investigated. Mixtures of the slag with kaolinitic clays and quartz can be used for cast ceramic articles up to 1 cm. in thickness.

400. Use of granulated phosphorus slags in cement production:
PARIMBETOV, B.P., TULESHOV, U.T. and SADUAKASOV, A.S.:
Vestn. Akad. Nauk. Kaz. SSR, 1973, 29(10), 44-47; (in Russian); Chem. Abs., 1974, 80, 51770.
[See also Ref 401]

401. Use of electrothermal phosphate slag for obtaining cement-like clinkers:
SADUAKASOV, A.S., PARIMBETOV, B.P. and TULESHOV, U.T.:
Vestn. Akad. Nauk. Kaz. SSR, 1973, 29(2), 39-42; (in Russian); Chem. Abs., 1973, 78, 150560.

402. Structure and hydraulic activity of slag glasses containing phosphorus and fluorine:
VED', E.I., SATARIN, A.V. and SHCHETKINA, T.YU.:
Tsement, 1973, (6), 21: (in Russian).
Silicate slags were synthesized similar in composition to those obtained from electrothermal production of phosporus. Their structure and the effect of the presence of P_2O_5 and F were studied by electron paramagnetic resonance.

403. Use of electrothermal phosphorus slag for production of water-resistant magnesia cement:
VED, E.I., BLUDOV, B.F. and PIVEN, N.:
Budiv. Mater. Konstr., 1973, 15(3), 44-45; (in Ukrainian);
Chem. Abs., 1973, 79, 149089z.
A durable white cement was produced from dolomite and 20% or more of electrothermal phosphorus slag.

[See also Refs 533, 565, 585, 593, 648]

IC 41/69

USE OF SLAG IN CEMENT PRODUCTION: NOTES ON A VISIT TO JAPAN AND AUSTRALIA

by R W Nurse

SUMMARY

After the V Symposium on the Chemistry of Cement (Oct. 1968) a few Japanese and Australian cement works were visited. Two points relevant to slag disposal were noted:

(1) Use of metallurgical slags (e.g. copper slag) as a component of cement raw meal.

(2) Marketing of a range of slag cements from ground granulate upwards by making use of air blending plant.

In an appendix a shortened translation of an E German report on the use of copper and zinc slag in cement is given.

A205/64/138/1
July, 1969
RP M39/68

Ministry of Public Building and Works
Building Research Station
Garston Watford Herts.
Telephone: Garston 74040

USE OF SLAG IN CEMENT PRODUCTION: NOTES ON A VISIT TO JAPAN AND AUSTRALIA

by R W Nurse

After the V Symposium on the Chemistry of Cement (Oct. 1968) a few Japanese and Australian cement works were visited. Two points relevant to slag disposal were noted:

(1) Use of metallurgical slags (e.g. copper slag) as a components of cement raw meal.

(2) Marketing of a range of slag cements from ground granulate upwards by making use of air blending plant.

In an appendix a shortened translation of an E German report on the use of copper and zinc slag in cement is given.

Cement Raw Meal

Both in Japan and Australia copper slag is added to some cement raw meals in order to increase the Fe_2O_3/Al_2O_3 ratio. A typical slag analysis would be:

SiO_2	36.8
Al_2O_3	6.3
Fe as Fe_2O_3*	48.5
CaO	6.1
MgO	1.0
SO_3	1.6

* Gain on ign 4.7 ∴ much FeO.

A205/64/138/1
Note No. IC 41/69

At the Gifu works of the Sumitomo Cement Co the raw meal proportions were:- Limestone 1220, Clay 320, Copper Slag 30, Kg per tonne of cement. So for their annual production of 1,600,000 they take 48,000 tonnes of slag. The Isa plant of Ube Industries also uses the slag (annual production 1,000,000 tonnes of cement). In Australia the Southern Portland Cement Co uses copper slag in making low heat type cement.

It is normally considered undesirable to have large amounts of ferrous iron in cement clinker, but no difficulties seem to be encountered in using copper slag. The Gifu plant has five oil-burning Lepol kilns, the Isa plant 10 Loesche vertical kilns and the Southern Co's plant 3 large rotary kilns, so the material is not specific to one burning process.

The cement plant of the Yawata Iron and Steel Co uses granulated slag as a constituent of the cement raw meal.

Granulated Blastfurnace Slag

Five and a half per cent (2,300,000 t) of Japanese annual cement production is blastfurnace cement, and 4.3% is fly ash cement. The desirable analysis of the slag gives

$$\frac{CaO + MgO + \frac{1}{3}Al_2O_3}{SiO_2 + \frac{2}{3}Al_2O_3} = 1.18$$

Some plants (e.g. Yawata) produce dry ground granulate and sell it as such or blended in a Fuller air merge plant to any given proportion with Portland cement. The same plant produces a fly ash blend.

A similar arrangement, but using an old tube Mill as mixer, is used at the Southern Cement Co in Sydney. The analyses of their materials are:-

Table 1

	Cement	Granulated slag	P.F.A.
SiO_2	20.0	32.8	62.2
Al_2O_3	6.1	21.6	25.4
Fe_2O_3	3.2	nil	3.1
FeO	nil	3.2	nil
MnO	nil	0.4	nil
TiO_2	0.3	0.7	nil
CaO	65.8	38.6	6.7
MgO	0.7	0.9	0.4
SO_3	2.4	nil	nil
S	nil	0.8	nil
Na_2O	0.03	0.30	0.05
K_2O	0.25	0.50	0.10
loss	1.3	nil	1.8

The physical properties of mortar and concrete including heat of hydration are given in table 2.

Cement	Mixture			Setting Time		Const. of Volume	Surf. Area	Compressive Strength LB/IN^2 Concrete								Slump	Conc. Mix Temp.	Ratios			Heat of Hydration
	Cement	HFP	Fly Ash	Initial	Final			Mortar			Standard Curing				Field Curing 33-72°F							
								3	7	28	3	7	28	90	3	7	28	90						7	28
								days			days				days								days	
A	100	Nil	Nil	1-15	2-30	1.0	3450	7100	8800	10350	2340	3520	5120	5620	1820	2960	4280	4760	2½"	70°F	0.65	-	-	89	101
"	85	15	-	1-30	2-45	0.9	3450	6200	8100	10200	2180	3260	5180	6080	1540	2340	3540	4200	2½	70	0.81	0.64	-	74	92
"	80	20	-	1-30	2-45	"	3450	5900	7800	9850	1780	2740	4990	6170	1660	2540	3580	3880	2½	70	0.80	0.64	-	68	89
"	75	25	-	1-30	2-45	"	3450	5950	7950	10300	1580	2580	4820	5660	1580	2500	3620	4360	2½	70	0.85	0.64	-	63	87
"	70	30	-	1-45	3-00	"	3450	5650	7650	10350	1580	2360	4600	5600	1500	2300	3430	4080	2½	70	0.90	0.63	-	59	83
"	50	50	-	2-15	3-30	"	3450	4200	6550	10000	1100	2000	4750	6400	800	1540	2660	3100	3½	70	1.23	0.61	-	57	68
"	80	-	20	2-15	3-00	"	3480	3900	5800	8450	1780	2420	3620	4680	1460	2140	3220	3920	2½	73	0.83	-	0.66	44	82
"	75	-	25	2-15	3-00	"	3490	3600	5250	7500	1500	2260	3140	4200	1300	1980	2980	3510	2½	73	0.89	-	0.67	35	66

Surface Area

Cement 3450 cm^2/g

HFP 3450 "

Fly Ash 3800 "

Appendix

New ground-in cement additives in the German Democratic Republic

Dr. Ing. Peter Greuling

(Contribution to the conference on cement production Varna 1968)

Table 3 gives the types of cement produced in the DDR and the annual production. Table 4 gives the breakdown of materials used.

Table 3

Type of Cement	Slag content %	Annual production (1000 tonnes p.a.) 1965	1966	1967
1. Portlandzement				
PZ 450	0	-	291	28
PZ 400	0	-		507
PZ 350	0	1242	956	1019
2. Eisenportlandzement				
EPZ 350	1 - 15	2298	2248	2550
EPZ 225	16 - 40	346	339	326
3. Hochofenzement				
HOZ 225	41 - 48	1706	2074	2183
4. Sonderzement				
SPZ 300	0	124	126	136

Table 4

	1964	1965	1966
Clinker	3860	4080	4204
Granulated Slag	1085	1104	1081
Nickel Slag	-	25	125
Copper Slag	-	-	100

Increasing use of richer ones and corresponding fall in the slag volume has led to a shortage of granulated slag and the cement industry can no longer look to this source for increased production. For this reason the Institute for the Cement Industry at Dessau has tested copper and nickel slags as cement additives, and also pulverized fuel ash. Up to 15% of copper or zinc slag was added and the product was classified as EPZ 350.

The slags are very acid, the range of analysis being shown on Table 3.

Table 5

	Nickel Slag	Copper Slag
SiO_2	48.0 - 53.8	46.9 - 49.5
Al_2O_3	8.7 - 11.0	15.5 - 19.4
Fe_2O_3	4.0 - 6.4	2.9 - 6.8
CaO	3.2 - 11.2	17.7 - 19.6
MgO	20.2 - 24.3	6.5 - 7.4

Very little is known of the reactions which take place; the glassy phases and monticellite are thought to be broken down by the alkalinity of the Portland cement. The rest of the crystalline matter (pyroxene and spinel) is inert.

3 million tons of cement with nickel slag and 1 million tons of cement with copper slag were made in 1965 - 1966, with the following mortar properties:-

Cement with 10% of:-

	Blastfurnace Slag	Nickel Slag	Blastfurnace Slag	Copper Slag
Fineness sq.cm/gm	3298	3529	2846	3201
Setting time:				
Water	28	28	26	26
Initial	3.35	3.55	3.40	3.35
Final	4.55	4.55	4.45	4.10
Expansion, Le Chatelier mm.	1.0	1.0	3.5	4.5
Tensile St. Kg/cm^2				
3 days	50	50	44	43
7 days	62	74	64	60
28 days	76	86	86	85
360 days	84	88	85	87
Compressive St. Kg/cm^2				
3 days	252	240	189	274
7 days	304	369	379	325
28 days	397	433	466	429
360 days	499	530	564	519
Shrinkage mm/m				
14 days	0.28	0.22	0.32	0.16
21 days	0.49	0.38	0.52	0.30
28 days	0.60	0.48	0.65	0.35
99 days	0.89	0.72	1.00	0.68
180 days	0.92	0.78	1.06	0.74

The rest of the paper deals with ash from brown coal.

LIBRARY TRANSLATION No. 1917

THE USE OF NICKEL SLAGS FOR MAKING STOWING MIXTURES

(Primenenie nikelevykh shlakov dlya prigotovleniya zakladochnykh smesei)

by

L V Chalyi, V T Kravchenko and E O Shternbek

Gron. Zh, 1974, 150 (2), 38-39

Translated from the Russian

Not for publication

Building Research Establishment
Garston, Watford WD2 7JR
Telephone: Garston (Herts) 74040

May 1975
A13

Although industrial waste materials such as blastfurnace slags, power station fly ash, burnt concentration tailings, etc., are mostly used as binders in the mixtures used for stowing in mine workings, Portland cement, which is both expensive and in short supply, continues to be used to a considerable extent.

More effective use may be made of the activity of Portland cement and its consumption reduced, by adding finely ground active additives to the stowing material, thereby greatly improving the fluidity, cohesion and homogeneity of the mixture during transportation through pipelines and enabling it to spread more freely and fill the worked-out space more efficiently.

The need to reduce the consumption of Portland cement and achieve complete utilization of its activity has become a matter of particular urgency at the Noril'sk Mining-Metallurgical Combine, which receives a large proportion of its Portland cement from the central regions of the Soviet Union, with the result that the cost of delivering the cement is actually greater than the cost of the cement itself. The Noril'sk industrial region being one where no active mineral additives are available, considerable interest attaches to the utilization of nickel melt slags, which are produced in quantities that may be sufficient to meet all stowing needs.

Though there is no unanimity with regard to the problems of using granulated nickel slag as a microfiller, the diversity of the conclusions, reached by a number of authors [1-3], is due in part to some differences in the chemical and mineralogical compositions of the slags under investigation.

The research reported here was carried out with a view to determining the optimum slag content in the binder composition for making stowing mixtures and to examining what effect the fineness of grinding of the slag constituent has on the cement activity. Wet-granulated nickel slag was used in the investigations. Its density was 3.1 - 3.2 g/cm^3 and bulk density 1.85 - 1.95 t/m^3. When rapidly cooled, it fails to crystallize and, instead, sets in vitreous form.

According to the classification of the Russian Standard GOST 3476-60, nickel slags cannot be regarded as a raw material for the production of binders. Their $(CaO + MgO)/(SiO_2 + Al_2O_3)$ ratio is 0.32 and their activity modulus 0.25. When determining the hydraulicity in compliance with GOST 6269-63 by the solution lime absorption method, one g slag was found after 30 days to have taken up 52.6 mg CaO, thus indicating that the slag is not without some activity.

The accompanying table shows the chemical composition of the metallurgical works' slag, the cement works' clinker and the gypsum.

The calculated mineralogical composition of the clinker is 49.5% C_3S; 23.4% C_2S; 12.9% C_3A; 11.6% C_4AF. The SO_3 content in the cement, consisting of clinker and added gypsum, is 2.64%. The cements tested were prepared by mixing the separately ground components. The grinding and mixing were performed in a laboratory ball mill. The specific surface of the purely clinker binder in every composition was 2900 cm^3/g.

The slag was ground to a specific surface of 2700 cm^2/g (10% residue on sieve No.008) and 3400 cm^2/g (5% residue) in the first and second series respectively. The test bars were made and tested in compliance with GOST 310-60, the properties determined being the setting times, normal consistence, ability to spread and soundness. The water/cement ratio in every case was 0.4. The slag content was varied as between one test bar series and the other.

(81048)

The test results were used to determine the relationship between the cement activity and the slag content and fineness of grinding for different hardening times (see Figure). Analysis of the data obtained shows that all binder compositions give a substantial increase of strength with prolonged hardening.

The strength factors fall much less at age 6 months than at 28 days, when the slag content is as much as 40%. Increasing the content beyond this value produces a more marked fall of strength. This is particularly noticeable when the slag is ground to a surface area of 3400 cm^2/g. When the slag content in the cement is high, the amounts of lime liberated during the hydration of the clinker component appear to be insufficient to bind all the slag, part of which remains free, as an inert microfiller. For this reason, it is best, when making binders of a similar type, to use clinker with an extra high C_3S content.

The comparative increase in the cement activity with increased slag content at the late hardening times may be due to the presence of low-basic calcium silicate hydrates, which require a long time for their formation. Thus, the nature of the change of the strength factors with time shows nickel granulated slags to be capable with prolonged hardening of actively reacting with the clinker constituent of the cement.

The increase in binder activity produced by increasing the fineness of grinding of the slag constituent is negligible. Since the time taken to grind the slag in the second test series was half as much again as in the first series, there is obviously little to be gained by grinding the slag constituent to a particularly fine state.

The unit power costs for grinding the slag are 1.65 times higher than for grinding the clinker. Chemical analysis of the residue on the No.008 sieve of the works-ground cement in a mill 2.6 x 13 with 40% slag addition showed over 70% of the residue to be slag. Consequently, with combined grinding the clinker is ground more finely, thereby enabling its activity to be used more effectively.

A feature of note is the low water requirement of the slag constituent. When the slag addition is increased, the normal consistence is reduced, and the ability to spread increases. A greater increase of cement activity may, therefore, be expected with a high slag content than with a purely clinker content, for the same mortar plasticity. All the specimens passed the test for soundness.

The industrial test and the subsequent introduction at the "Mayak" mine of stowing material made with cement, to which ground granulated slag was added to the amount of 30 - 40%, showed the stowing mixture to be satisfactorily transported through pipelines over large distances and the consolidated fill to possess the required strength.

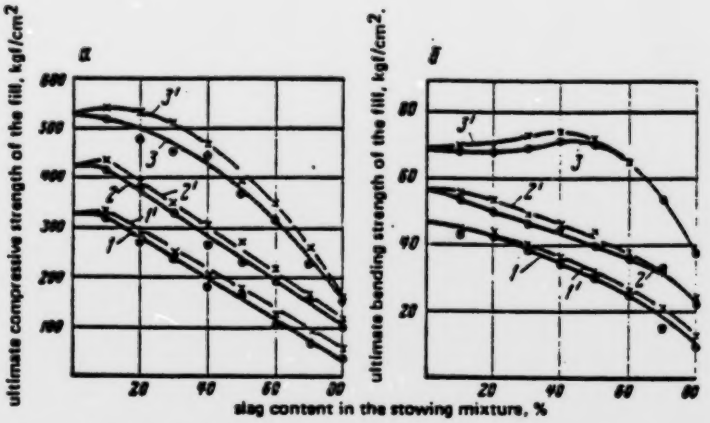
The inclusion of nickel slag in the stowing mixture compositions has reduced the consumption of cement, which is in short supply, by between 100 and 120 kg/m^3, depending on the grade of stowing.

References

1. B A Goloshchapov et al.: Obtaining consolidating mixtures from non-ferrous metallurgy slags. Gornyi zhurnal 1970 (6), 36-7.
2. V I Yakubov and N V Ivanova : Nickel slag - an effective mineral additive. Tsement 1971 (12), 16-7.
3. V A P'yachev et al.: Cement compositions for concretes intended for steam-curing. Tsement 1972 (11), 22-3.

Table Chemical composition of the materials, %

material	loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	SO_3
clinker	0.16	21.02	7.30	3.82	-	65.04	2.2	0.28
slag	-	41.3	10.49	2.31	27.2	6.42	10.52	1.34
gypsum	21.49	1.34	0.44	0.41	-	32.25	1.68	42.7


а
б
ultimate compressive strength of the fill, kgf/cm²
ultimate bending strength of the fill, kgf/cm².
slag content in the stowing mixture, %

Graphs of relationship between the activity of the cement and the slag content and fineness of grinding: a — compressive strength of fill specimens; b — bending strength; 1 — 3 — fineness of grinding up to 10%; 1' — 3' — the same, up to 5%.

Chapter IX

NON-FERROUS SLAGS

IX.1 Introduction

The non-ferrous slags considered here - copper, lead, lead-zinc, nickel, phosphorous, and zinc - are those that appear to be produced in quantities that make potential road construction applications attractive.(1, 2)* In fact, the many uses for these slags that have been developed often puts them in the general class of by-products with useful applications, rather than just wastes that must be disposed of. Boiler and pyrolysis slags have not been included in this section, but they share many properties and applications with the non-ferrous slags.(3, 4) (Only very small quantities of aluminium and tin slag are produced.)(2)

IX.2 Copper Slag

IX.2.1 General properties

Copper slags are usually discharged from the furnace at 1,100 to 1,300°C and when cold have a black colour and stony, or glassy appearance. As a rule, the specific gravity will vary with the iron content, from a low of 2.8 to as high as 3.8. Some typical compositions are shown in Table IX.1. While slag generation is highly dependent on specific processes and sources, it may be as high as 4 tonnes of slag/tonne of copper produced. For instance, production of copper slag in the United Kingdom is approximately 100,000 tonnes (secondary smelting) while that in the United States is approximately 7 million tonnes (mainly primary smelting). A typical slag from a primary copper smelter is dumped in a molten state or granulated. Recycling for extraction of metal values is common.

Table IX.1

ANALYSIS OF COPPER SLAG (in %)

Process	Cu	SiO_2	FeO	CaO	Al_2O_3	MgO	S
Blast furnace	0.35	33.0	46.5	6.75	8.1	-	0.45
Reverberatory slag	0.37	36.6	35.3	2.0	8.1	-	0.7
Converter	-	27.7	42.8	2.4	0.6	0.7	-

IX.2.2 Applications

Non-Road Uses (Competing Uses)

Sand blasting. It would appear that much copper slag, particularly from secondary smelting, is highly suitable for sand blasting.(2) For countries with fairly low production levels, this usage will probably take most of the available copper slag.

Cemented mine black-fill. Current research has shown that several non-ferrous slags (copper, lead, and nickel) have great potential as pozzolans for use in cemented mine back-

* See references at the end of this chapter.

fills, with appreciable cost savings over straight Portland cement fill.(5, 6) It has also been suggested that a similar cementitious blend of finely ground copper or nickel slag and Portland cement could be used as the binder for base stabilization in road construction.(6) A summary of the available information on ground non-ferrous slag (copper, lead, and nickel) - Portland cement binders indicates the following: 1) the slag must be vitrified; 2) the slag must be finely ground; 3) the slag content of the binder must not be too high or reactivity is limited; and 4) the slags act as pozzolans with a relatively slow reactivity.

Railway ballast. In areas where large amounts of copper slag are available, it would appear that use as railway ballast is common.(7) For instance, in Canada copper slag from Noranda has been used with good success as railway ballast since 1968. Copper-zinc slag from Flin Flon was first tried in track, with indifferent results, in 1972.

Current Uses in Road Construction

Granular fill and base material. It would appear that the only significant current use of copper slag in road highway construction is as granular fill and base material. This usually involves crushing and sizing to ensure adequate compaction. As with most non-ferrous slags, potential leachate problems should be evaluated before use (Chapter XX, Appendix A). The main reason why more copper slag is not used as granular fill and base is the often remote location of copper production from road construction sites and the high unit weight of copper slag. This is particularly the case in Canada and the United States where large volumes of copper slag are generated.

Potential Uses in Road Construction

Base stabilization. The potential use of finely ground copper slag combined with Portland cement as the binder in a base stabilization process should be investigated. A similar process has shown great promise for cemented mine back-fill as indicated in the non-road uses section. Research approaches could follow those used to study the use of vitrified blast furnace slags in base stabilization.(8) The potential energy and cost savings in such uses are significant.

Bituminous concrete. It should be possible to use copper slag as an aggregate in bituminous concrete. This could be studied in the same way as steel slag, which is now a widely used aggregate in bituminous concrete.(9) It is understood that some work on the use of copper slag as aggregate in both Portland cement and bituminous concretes has been completed in the United States.(1)

Portland cement concrete. The use of copper slag or aggregate in concrete is questionable.

IX.3 Lead, Lead-Zinc and Zinc Slags

IX.3.1 General properties

Since lead and zinc are often related as co-products in both source and metallurgical treatments, the various combinations of these non-ferrous slags - lead, lead-zinc and zinc - will be considered as one group.(1, 2) Slags of this group are often black or red in colour, cohesionless, glassy and have sharp angular particles that are cubical in shape. The specific gravity tends to be as high as 3.6. Some typical compositions are shown in Table IX.2. Slag generation is highly dependent on specific processes and sources, and generally speaking, the quantities available are relatively small. For instance, 60,000 to 70,000 tonnes of lead-zinc slag are produced in a granular form by Imperial Smelting Processes Incorporated (ISP) at their smelter in the United Kingdom (lead-zinc slag in Table IX.2).

Table IX.2

ANALYSES OF LEAD AND LEAD-ZINC SLAGS (in %)

Slag	CaO	SiO_2	FeO	Al_2O_3	MgO	BaO	PbO	MnO	S
Lead	22.2	35.0	28.7	-	-	-	-	-	1.1
Lead-zinc	19.5	17.6	35.9	6.1	1.3	2.0	0.8	2.0-3.0	2.8

IX.3.2 Applications

Non-Road Uses (Competing Uses)(2)

Sand blasting. Lead-zinc slag is used for this purpose.

Fill. Lead-zinc slag is suitable for bulk fill for land development.

Calcium silicate bricks. ISP have shown that their lead-zinc slag can be used in the manufacture of sillicate bricks.

Other uses, such as water filtration medium and in night-storage heaters have been investigated.

Current Uses in Road Construction

Bituminous concrete. A road trial was carried out in Bristol, United Kingdom, to evaluate the use of lead-zinc slag as the fine aggregate in bituminous concrete with limestone as the coarse aggregate. The wearing properties were good, but the skid resistance was only moderate.(2) Results from tests in Oklahoma, United States, of four types of zinc smelter wastes (fine slags) used as aggregates in sand asphaltic concrete mixes, and asphalt stabilized base, indicate that they are suitable for these aspects of highway construction. Since the material tends to be uniformly graded, the addition of very fine sand may be required in asphaltic mixes.(10) These smelter wastes should improve the skid resistance of mixes based on limestone aggregate.

Potential Uses in Road Construction

Portland cement concrete. Lead-zinc slag has not generally been used as a concrete aggregate, possibly due to its high density ($\simeq$ 2,000 kg/m^3). However, a licensee of ISP in Japan sells 20 to 25 per cent of its lead-zinc slag for use as an aggregate in concrete.(2) Specific use in concrete for road construction is not known of. As far as zinc slag is concerned, results from the Oklahoma tests indicate that the smelter wastes considered cannot be used in Portland cement concrete because of potential cement/aggregate reactions.(10) This problem (and the use of lead slag) should be further researched.

Granular fill and base material. Lead, lead-zinc, and zinc slags should generally be usable in fill construction and as base materials. However, they are often produced at some distance from road construction projects and their high unit weights increase transportation costs. Potential leachate problems would have to be evaluated (Chapter XX, Appendix A).

IX.4 Nickel Slag

IX.4.1 General properties

The use of nickel slags in highway and railway construction has been the subject of a fair amount of research in Canada.(6, 7, 11) The iron-silicate slag is dumped, and allowed to air cool so that a "clinker" is formed. This material is then crushed and processed as required, but the quantity of fines produced tends to be low. The specific gravity tends to be as high a 3.5. A typical composition is shown in Table IX.3. Current annual nickel slag production in Canada is approximately 950,000 tonnes (approximately 0.20 tonnes of

slag/tonne of copper-nickel ores and concentrates, or approximately 4 tonnes of slag/tonne of nickel produced). United States production of nickel slag is approximately 725,000 tonnes, or approximately 60 tonnes of granulated nickel slag/tonne of nickel, a very high general ratio.

Table IX.3

ANALYSIS OF NICKEL SLAG (in %)

Slag	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	SO_3	S
Sudbury	29.0	trace	53.06	3.96	1.56	trace	0.36	1.04

IX.4.2 Applications

Non-Road Uses (Competing Uses)

Sand blasting. Granulated nickel slag is used for this purpose.

Cemented fill. See Copper Slag section on this topic.

Railway ballast. Nickel slag from Sudbury, Canada, has been used for 25 years as railway ballast and has established itself as being the best material used. The processed slag is heavy (specific gravity of 3.2 to 3.6), tough, hard, angular, and packs well under ties to form a better support for track than rock ballast. Slag placed in track over 20 years ago is still in good condition. However, the density of the slag means that transportation on a volume basis is more expensive than rock ballast. More energy is required to compact the material into the track bed; however, the resulting stability is a valuable asset. This slag meets or exceeds typical specifications for rock ballast.

Current Uses in Road Construction

Granular fill and base material. See Copper Slag section on this topic.

Anti-skid material. Nickel slag produced in Oregon, United States, is light in weight and appears to possess hardness and abrasion resistance. Only small quantities are used for this purpose.

Potential Uses in Road Construction

As regards base stabilization and bituminous concrete, see Copper Slag section on this topic.

IX.5 Phosphorous Slag

IX.5.1 General properties

This section draws heavily on the production and usage of phosphorus slag in the United States.(12, 13) At most elemental phosphorus plants, molten slag is tapped into a pit, air-cooled or cooled by applying water on the slag surface, and the material is then crushed for use as ballast or aggregate. However, both granulated and expanded phosphorus slags are produced, and there have been some experiments with pelletizing in the United States. A typical analysis for phosphorus furnace slag is given in Table IX.4. While slag generation is highly dependent on specific processes and sources, it may be as high as 8.2 tonnes of slag/tonne of elemental phosphorus produced. Crushed air-cooled phosphorus slag has a bulk density of 1,360 to 1,440 kg/m^3, granulated phosphorus slag has a bulk density of about 1,120 kg/m^3 and expanded phosphorus slag has a bulk density of 880 to 1,000 kg/m^3.(13) (Most phosphate rocks contain between 30 and 200 ppm uranium, and most of this uranium comes out in the phosphorus furnace slag. However, Tennessee Valley Authority tests show that radiation is negligible and presents no hazard.) Current United States annual production is approximately 3.6 million tonnes.

Table IX.4

TYPICAL ANALYSIS OF
PHOSPHORUS FURNACE SLAG (in %)

CaO	SiO_2	Al_2O_3	P_2O_5	F	K_2O
44.1	41.3	8.8	1.3	2.8	1.2

IX.5.2 Applications

Non-Road Uses (Competing Uses)

While many of the applications have only been at the experimental stage, the present and potential uses for phosphorus slag closely parallel those for iron blast furnace slag.: crushed air-cooled phosphorus slag (block aggregate, concrete aggregate, slag wool production, railway ballast granular fill, granular base, bituminous concrete aggregate); granulated phosphorus slag (agricultural, cement manufacture); and expanded phosphorus slag (lightweight aggregate, block aggregate). From this listing, it is clear that road applications will have to compete with a wide range of other uses, but transportation costs from production areas to construction areas will probably be the governing factor.

Current Uses in Road Construction

Granular fill and base material. Phosphorus slag has been used in large quantities in Montana, United States (Butte area), for aggregate in base courses.(1)

Aggregate in bituminous concrete and Portland cement concrete. Similar to iron blast-furnace slag.

Potential Uses in Road Construction

Base stabilization. Granulated (or pelletized) phosphorus slag may be suitable for use in base stabilization. See Copper Slag section for general comments on this topic.

IX.6 Summary

The non-ferrous slags discussed - copper, lead, lead-zinc, nickel, phosphorus and zinc - all appear to have existing bulk applications in road construction. However, production points are often remote from road construction demand points, and high unit weights are often involved. The main area of research required on non-ferrous slag use in road construction appears to be in base stabilization, where pozzolanic or cementitious reactions can be used to advantage with a substantial energy saving over the usual cementing agents. Potential leachate problems associated with fill, base and embankment applications of non-ferrous slags must always be evaluated prior to utilisation.

References

1. MILLER, R.H. and COLLINS, R.J. Waste materials as potential replacements for highway aggregates. Report 166, NCHRP, Transportation Research Board, Washington, 1976.
2. CUTT, W., NIXON, P.J., SMITH, M.A., HARRISON, W.H. and RUSSELL, A.D. A survey of the locations, disposal and prospective uses of the major industrial by-products and waste materials. CP19/74, Building Research Establishment, Watford, 1974.
3. SIKES, P.S. and KOLBECK, H.J. Disposal and uses of power plant ash in urban areas. Journal of the Power division, ASCE, Vol. 99, No. PO1, pp. 217-234, May 1973.
4. DAVIDSON, P.E. Slagging pyrolysis solid waste conversion. Engineering Digest, pp. 31-34, August, 1975.
5. THOMAS, E.G. A review of cementing agents for hydraulic fill. Jubilee Symposium on Mine Filling, Australian I.N.M., Mount Isa, pp. 65-75, August, 1973.

6. LANEUVILLE, J. Portland cement-slag binders. Canadian Patent No. 963482, St. Lawrence Cement Company, 25th February, 1975.
7. FEASBY, D.G. Mineral Wastes as Railway Ballast. Mineral Sciences Laboratories Report MRP/MSL 75-76 (OP), CANMET, EMR, Ottawa, April 1975.
8. EMERY, J.J., KIM, C.S. and COTSWORTH, R.P. Base stabilization using pelletized blast furnace slag. Journal of Testing and Evaluation, ASTM, Vol. 4, No. 1, pp. 94-100, January 1976.
9. EMERY, J.J. New Uses of Metallurgical Slags. The Canadian Mining and Metallurgical Bulletin, CIM, Vol. 68, No. 764, December 1975.
10. HUGHES, M.L. and HALLIBURTON, T.A. Use of zinc smelter waste as highway construction material. Highway Research Record, No. 430, pp. 16-25, 1973.
11. WRONG, G.A. Experience with Inco slag for highway construction purposes. Report No. 14, Materials and Research Section. Department of Highways, Ontario, January 1960.
12. BURT, R.B. and Barber, J.C. Production of elemental phosphorus by the electric-furnace method, Tennessee Valley Authority, Knoxville, 1952, reprinted 1967.
13. MANTELL, C.L. Solid wastes: origin, collection, processing, and disposal, John Wiley, New York, 1975.

THE ACTIVITY OF HIGH MAGNESIA NICKEL SLAG

Chen Zhi-yuan, Associate Professor
(Department of Materials Science and Engineering
Tongji University, Shanghai)

Abstract

The slag obtained from the process of extracting nickel from serpentine contains a high proportion of magnisia (about 40%) and has a lower activity. This paper describes mainly the results of the study on regulating the slag compositions during the metallurgical process to meet the requirements of supersulphated cement.

The results show that, after adding limestone and others to the metallurgical raw materials and keeping controlling the composition of slag in a certain range, the activity of the quenched slag was raised without any influence on the soundness of the slag, and, at the same time, the quantity of nickel obtained also was raised.

The optium components of the HMNS supersulphated cement are discussed in this paper. The cement hydrated well and had enough strength. Using X-ray powder method, DTA, EM and SEM we found that ettringite and C-S-H gel were the main hydration products. The hydration mechanism of the cement is also discussed.

made. In Britain for example the slag is allowed to weather for at least 6 months. In Germany, according to a preliminary limitation, steel slags are only used for bituminous surface layers and binder courses if they have less than 4 wt. % of free lime.

Expansion tests on steel slags carried out in Canada [34] have shown that elevated temperatures greatly increase the amount of expansion: at 82°C expansion was about three times as great as at 60°C, that the fine particles of lime cause the greatest expansion and that significant reductions in the total amount of expansion could be achieved by treating the slag with acid (spent pickle liquour). Canadian experience also shows that when the slag is used in asphaltic mixes which are relatively impervious to water the problems of expansion are much reduced. If the finer sizes of slag (minus 10 mm) are used ageing prior to use is not necessary while for coarser sized material a minimum ageing period of 30 days is recommended in Canada.

2.3.1.2. Use in stabilised base courses

Steel slag is used in the Netherlands in stabilised base coarse construction 25% of BOF slag (0-15 mm) is mixed with 60% air cooled blastfurnace slag (0-60 mm) and 15% granulated blastfurnace slag [2].

2.3.1.3. Use in wearing courses

Because of its properties of high density, angularity and strength, steel slag has been found to be an excellent aggregate for bituminous mixes and is used in this way in several countries including Canada, UK, Italy and the USA [2]. Bituminous concrete wearing courses containing steel slags have been found to have excellent stability and flow, very good surface characteristics with in particular very high skid resistance properties, very good resistance to stripping and to be easy to compact. The high density does however mean high transport and bitumen costs.

2.3.2. *Other uses*

Where the steel slag has an appreciable phosphate content there is a valuable market as a fertiliser but the quantities of such slags have decreased in recent years. Some attempts have been made to use low phosphate slags in this way by mixing or intergrinding them with sources of phosphate such as high phosphate slags or phosphate rock.

In Australia high manganese slags have been used experimentally as a source of manganese dioxide in the manufacture of coloured bricks.

From India it is reported that electric arc slag is being granulated and sold for use in cement manufacture and in Japan steel slag is also reported to be used in Portland cement manufacture. No details of these processes are available. In Europe it has generally been found that steel slags are not in the right composition range to granulate successfully and that the presence of metallic iron makes such an operation hazardous.

2.3.3. *Uses under development*

The main uses of steel slag under development are in road making, particularly in the wearing coarses. Attention is being given to the control of expansion by study of the weathering process and by accelerated methods of weathering.

From India it is reported that the use of steel slags in the calcium silicate products is being investigated.

There have been reports in the literature of attempts to produce a steel slag with hydraulic properties by adjusting the composition of the melt. The incentive for this is that many high lime steel slags have a chemical and mineralogical composition like that of a weak cement clinker and may even contain small amounts of tricalcium silicate, the main cementing phase in Portland cement.

3. OTHER METALLURGICAL SLAGS

The main metallurgical slags other than those produced during the smelting of iron and steel are the ferro alloy slags from the manufacture of specialist steel-alloys and those from the smelting of copper, lead, zinc, nickel and tin. In addition there are slags from iron foundries and slags produced in the manufacture of phosphorus.

3.1. Composition

The chemical analyses of some metallurgical slags are compared in table VIII. They vary considerably according to the particular ore being used but all the non-ferrous slags have high iron content. Many of these slags are granulated and are therefore vitreous in form but it is reported that a South African copper slag consists mainly of the mineral fayalite (Fe_2SiO_4) with some feldspar.

The relative densities of the slags vary according to their iron content but tend to be high (around 3.5). They are mostly dark coloured and glassy in appearance.

3.2. Quantities

The available information on the quantities of these slags is tabulated in table IX. Compared with the production of iron and steel slags the quantities are small.

3.3. Utilisation

The use of slags other than those from iron and steel manufacture is relatively undeveloped. The ways in which they are used are summarised in table X. The only extensive utilisation is for grit blasting; copper slags in particular are used in this way. In Canada considerable quantities of copper and nickel slags are used as ballast in railways. Nickel slag in particular is judged to form a better support for track than rock ballast although the high density of the slag makes transportation more expensive. There is some utilisation in road making, as fine aggregate, as a pigment and in the manufacture of ceramics but these probably only account for small quantities of the slags.

3.4. Uses under development

There is evidence from research that finely ground, vitrified slags from copper, lead or nickel smelting have some hydraulic properties and there is development work on the use of mixtures of such slags and Portland cement as cemented mine back-fills and for road base stabilisation.

The use of air-cooled phosphorus slag as ballast or aggregate has been developed in North America and granulated and expanded phosphorus slags are also produced.

TABLE VIII

COMPARATIVE PROPERTIES OF METALLURGICAL SLAGS
(CHEMICAL COMPOSITION IN WEIGHT %)

	Low carbon ferrochrome slag India	Charge chrome slag South Africa	Copper slag		Zinc slag Australia	Zinc/lead slag UK	Nickel slag Australia	Tin slag	
			USA	South Africa (*)				UK	USA
CaO	53.3	1.12	6	9.2	16.6	19.5	7.35	20-22	5
SiO_2	26.15	19.34	36	34	21.2	17.6	34.5	26	23
Al_2O_3	–	18.25	8	5.7	–	6.1	2.35	13	15
MgO	7.19	18.27		4.3	0.5	1.3	7.6	1.5	11
MnO	–	0.2	–	–	4	2-3	–	–	–
FeO	0.515	5.15	46	32.7 (*)	36.3	35.9	42.9	32-35	12
R_2O_3-Fe_2O_3	11-21	–	–	–	–	–	3.7	Heavy metal oxides	27
Cr_2O_3	4.715	5.19	–	–	–	–	–	–	–
SO_3	0.115	–	–	–	–	7	–	–	–
ZnO	–	–	–	–	7	–	–	–	–
PbO	–	–	–	–	1.1	0.9	–	–	–
BaO	–	–	–	–	–	2	–	–	–
Relative density	–	–	2.8-3.8		Up to 3.6		Up to 3.5	–	–

(*) From copper magnetite ore. Slag predominantly fayalite with some feldspars.
(*) Expressed as Fe, mainly present as FeO and Fe_2O_3.

Work has been carried out in India on the utilisation of low carbon ferrochrome slag and methods have been developed for producing slag cements and building blocks of moderate to high strength.

Some work has been carried out on the use of zinc/lead slags as aggregate in bituminous and asphaltic concrete where they appear to be satisfactory in most respects though with only moderate resistance to skidding.

Other uses which have been explored are as a water filtration medium, in the manufacture of calcium-silicate products and in night storage heaters. It is reported that zinc/lead slags are used as aggregate in concrete in Japan but American research suggests that there may be an alkali-silicate reaction problem.

A possible problem with the use of these non-ferrous slags is that they may contain components that are unstable in the presence of water so that water percolating through them may leak out harmful pollutants. An example of this happening with the slag from the refining of silver and platinum has been reported [35]. It seems inadvisable to build on old spoil heaps of slags which contain toxic heavy metals or to use such slags as fill under buildings.

4. DISCUSSION

Blastfurnace slag is the best established and best utilised by-product under consideration in this Symposium. Its uses as an aggregate in road construction and in dense or lightweight concrete are well established and covered by appropriate standards in many countries. It is also the best established by-product for use in cement and there are no technical problems or stability barriers to its use. Blastfurnace slag cements have advantageous properties over Portland cement in some circumstances and there are standards for many types of slag cement. New methods of processing such as pelletization will help to promote its use still further.

Steel slag is a much more variable material than blastfurnace slag and is liable to contain compounds such as free lime and magnesia which hydrate and expand when wet. Accordingly it is less used but can make a valuable contribution as a roadstone because of its skid resistant properties or as a fill in earthwork. To avoid disruption due to hydration it is necessary to weather it before use or to employ

TABLE IX

PRODUCTION OF METALLURGICAL SLAGS (Mt/yr.)

	Ferroalloy	Copper	Zinc	Lead	Nickel	Tin	Other	Stockpiles
India	0.214	0.164	–	–	–	–	–	2.5 Mt of ferroalloy slag
Australia	–	0.072	0.05	0.2	Unquantified	–	–	–
USA	Unquantified	5.2	Unquantified	–	0.725	Unquantified	4 phosphate 20 foundry (*)	–
South Africa	0.97	0.46	–	–	–	–	0.35 granulated platinum slag	3 Mt ferroalloy 3 Mt copper 6 Mt granulated platinum
Canada	–	1.9 Mt of nickel and copper slag			–	–	–	–
Finland	0.050	0.173			0.108	–	–	–
UK	–	0.1	0.06-0.07		–	0.074	–	–

(*) Includes foundry slag and dust.

it in situations where it is protected from moisture for example in bituminous concrete.

Non-ferrous slags are little used. The only extensive use is in grit blasting. Other uses have been explored but apart from technical difficulties the factors militating against their use are the relatively small quantities produced at any one location and the tendency in many cases for them to be produced in remote areas. There are also potentially problems of toxicity or pollution especially by the slags of heavy metals.

TABLE X

UTILISATION OF METALLURGICAL SLAGS

India

Ferroalloy slags: small quantities used as filler, as brick-making materials and as road aggregate in local construction potential established for making slag cement and autoclaved building blocks.

Copper slag: used as road making materials and for void filling in mines.

Australia

Copper slag: grit blasting and landfill.

Zinc slag: little used but shown to be satisfactory for grit blasting and in the manufacture of ceramics.

Lead slag: minor use in grit blasting and landfill.

USA

Phosphorus slag: as an aggregate and in ceramic tile manufacture.

Foundry slag: as a fine aggregate and as a pigment.

Zinc slag: as a fine aggregate.

South Africa:

Copper slag: grit blasting.

Canada:

Copper and nickel: used as railway ballast.

Belgium:

Zinc refining waste: iron oxide pigment produced for colouring concrete and asphalt.

UK:

Copper slag: grit blasting.

Lead/Zinc slag: landfill, fine aggregate.

Tin slag: grit blasting, road making material.

Finland:

Copper slag: grit blasting, brickmaking.

Nickel slag: grit blasting, brickmaking.

Ferroalloy: sanding of roads during winter.

CHAPTER 4

BY-PRODUCT GYPSUM

Calcium sulphate is produced as a by-product of such chemical processes as the manufacture of phosphoric acid, the neutralisation of waste sulphuric acid or pickling liquors, the production of hydrofluoric acid or the removal of SO_2 from flue gases. By far the biggest source is the manufacture of phosphoric acid by reaction of phosphate rock with sulphuric acid. There are a number of wet processes for doing this. The reaction can be illustrated by the equation describing the process carried out in Australia where the phosphate rock is relatively free of fluoride;

$$Ca_3(PO_4) + 3H_2SO_4 + 6H_2O \rightarrow 3CaSO_4 \cdot 2H_2O + 2H_3PO_4$$

Depending on the process conditions the calcium sulphate may be separated as either the dihydrate or the hemihydrate. Because of contamination with phosphates both products are usually termed phosphogypsum.

The amounts of by-product gypsum produced by the removal of SO_2 and SO_3 from flue gases are increasing, particularly in the USA and Japan. In the USA they mainly originate from coal burning power stations and are collected as a sludge with a solid content of between 19 and 50%. Both calcium sulphite and sulphate are formed. In Japan the emitted SO_2 and SO_3 is mainly from the burning of oil and while there are a number of SO_2 removal systems in operation the most common uses lime to trap the SO_2 as calcium sulphate.

1. COMPOSITION

The chemical analyses of some sources of phosphogypsum are listed in table I. The main impurities are phosphate and fluoride though these vary somewhat according to the source of the phosphate rock and the process used. Phosphogypsum also tends to contain traces of radium, the decay product of uranium found in the phosphate rock. Phosphogypsum derived from sedimentary phosphate ores has a relatively high level of radioactivity (of the order of 25 pCu/g radium) whereas that from igneous phosphate ores is generally an order of magnitude lower in radioactivity.

It is reported from South Africa that the moisture content of phosphogypsum in the dumps is 20 to 30% by weight. The particle size distribution of a South African phosphogypsum in given in table I.

No analyses of by-product gypsum from other sources have been reported.

2. QUANTITIES

The available information on the quantities of by-product gypsum produced and stockpiled and methods of disposal is summarised in table II. A breakdown of the production of gypsum from exhaust gas desulphurisation in Japan is given in figure 1. In countries where the waste gypsum is dumped on land considerable stockpiles have accumulated, parti-

APPENDIX B

DATA SUPPLIED BY INCO LIMITED, THOMPSON

B1	Furnace Granulated Slag Screen Analyses.
B2 to B5	Ledger (Weight and Chemical Analysis) for Furnace Slag (Ni Circuit, Cu Circuit and Total), January 1985 to March 1986.

THE INTERNATIONAL NICKEL COMPANY OF CANADA LIMITED
Manitoba Division

Memorandum

To R. G. ORR Date APRIL 1, 1976

From R. A. HESS (I. S. KAWULKA)

Subject FURNACE GRANULATED SLAG SCREEN ANALYSES

Samples of granulated furnace slag were gathered and submitted for screen analysis.

The samples were gathered from two locations:
1. the drop point at the end of #3 furnace slag line
2. the piles of slag beside the Mill

In all cases, the samples were grab samples. The results were as follows:

Mesh Size	#3 Furnace March 31, 1976 Wt. %	Mill Piles Grab #1 Wt. %	Mill Piles Grab #2 Wt. %
+10	0.9	5.0	3.9
+20	25.8	25.0	25.8
+35	57.3	47.7	47.5
+65	13.8	14.4	14.7
+100	1.5	3.2	3.3
+200	0.6	2.6	2.7
-200	0.1	2.1	2.1
Total	100%	100%	100%

R. A. HESS

RAH/id
xc: G. M. Brake
H. R. Straw
T. E. Fregren
File

LEDGER FOR FURNACE SLAG (NI CIRCUIT)

	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CD	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 85	34193.	0.330	0.225	0.036	0.081	34.600	1.140	36.300	154575.	24732.	55647.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.017
FEBRUARY 85	31582.	0.300	0.229	0.035	0.086	34.700	1.350	34.100	144646.	22107.	54321.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	29.499
MARCH 85	37481.	0.333	0.212	0.038	0.091	34.300	1.300	35.300	158928.	28497.	68219.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.059
APRIL 85	30227.	0.300	0.204	0.034	0.085	35.100	1.200	35.600	147806.	24634.	61586.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.776
MAY 85	36449.	0.333	0.192	0.040	0.078	34.100	1.200	37.100	139939.	29152.	58846.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.289
JUNE 85	33515.	0.300	0.190	0.039	0.075	33.800	1.200	36.900	127357.	26142.	50273.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.795
JULY 85	4996.	0.300	0.230	0.040	0.064	34.400	1.200	37.700	41382.	7197.	11515.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.365
AUGUST 85	14872.	0.300	0.173	0.031	0.040	30.300	0.900	35.200	51457.	9221.	11898.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	33.355
SEPTEMBER 85	21749.	0.300	0.262	0.037	0.066	31.900	0.900	38.300	113965.	16094.	28709.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.535
OCTOBER 85	32641.	0.300	0.140	0.034	0.056	33.600	1.200	37.100	124036.	22190.	36558.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.819
NOVEMBER 85	34130.	0.300	0.205	0.029	0.070	35.700	1.400	33.900	123558.	17479.	42192.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.694
DECEMBER 85	27945.	0.300	0.267	0.022	0.083	35.000	1.300	35.500	149226.	12296.	46349.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.327
TOTAL	342930.	0.300	0.213	0.035	0.076	34.305	1.212	35.977	1470860.	239737.	524131.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.181

LEDGER FOR FURNACE SLAG (CU CIRCUIT)	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CO	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 85	27d3.	0.000	0.293	0.257	0.139	37.400	1.000	33.400	16358.	14375.	7737.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	27.450
FEBRUARY 85	6691.	0.000	0.254	0.240	0.104	35.200	0.940	30.100	33990.	32920.	14453.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	33.151
MARCH 85	6723.	0.000	0.101	0.229	0.079	37.500	1.100	33.900	21055.	33331.	10025.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.530
APRIL 85	5049.	0.000	0.162	0.240	0.088	35.900	0.900	35.000	16359.	24235.	8886.	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	27.110
MAY 85	4747.	0.000	0.259	0.273	0.109	33.000	0.900	36.400	24589.	25919.	13343.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.158
JUNE 85	4747.	0.000	0.363	0.291	0.146	34.800	0.700	35.900	34995.	31521.	15815.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	27.801
JULY 85	1022.	0.000	0.250	0.210	0.140	37.600	0.700	32.500	8275.	6951.	3972.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.618
AUGUST 85	4727.	0.000	0.314	0.222	0.139	37.700	1.200	31.400	24686.	20988.	13141.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	29.024
SEPTEMBER 85	11301.	0.000	0.379	0.230	0.161	39.500	1.100	30.200	85662.	63286.	36389.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.379
OCTOBER 85	4017.	0.000	0.374	0.356	0.137	40.600	1.000	30.100	30047.	28631.	11007.	
	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	27.430
NOVEMBER 85	8143.	0.000	0.342	0.372	0.116	40.700	1.100	28.900	42292.	46002.	14345.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.469
DECEMBER 85	15916.	0.000	0.359	0.308	0.103	41.000	1.100	28.000	114277.	98043.	32787.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	29.128
TOTAL	74291.	0.000	0.307	0.282	0.119	38.272	1.005	31.292	462135.	423572.	179536.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.722

LEDGER FOR FURNACE SLAG TOTAL	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CD	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 85	371444.	0.330	0.230	0.083	0.085	34.810	1.134	36.033	173883.	39037.	63344.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.634
FEBRUARY 85	382733.	0.330	0.233	0.072	0.090	34.787	1.278	33.491	178636.	55327.	68774.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	30.137
MARCH 85	392988.	0.330	0.234	0.087	0.084	30.224	1.270	35.211	183383.	59238.	74845.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.130
APRIL 85	41276.	0.330	0.199	0.059	0.085	35.198	1.163	35.600	164165.	48869.	70472.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.695
MAY 85	41187.	0.330	0.200	0.067	0.082	34.905	1.131	37.165	164319.	55371.	67124.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.389
JUNE 85	33262.	0.330	0.211	0.070	0.084	33.924	1.138	36.776	160352.	57663.	66988.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.796
JULY 85	10021.	0.330	0.233	0.069	0.073	33.208	1.122	36.392	49657.	14148.	15447.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.405
AUGUST 85	19599.	0.330	0.207	0.077	0.064	32.085	0.972	34.283	81143.	30209.	25039.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	32.311
SEPTEMBER 85	33053.	0.330	0.302	0.120	0.098	34.479	0.968	35.530	199627.	79380.	65044.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.481
OCTOBER 85	30058.	0.330	0.210	0.069	0.065	34.367	1.178	36.333	154283.	50797.	47565.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	27.777
NOVEMBER 85	30319.	0.330	0.228	0.087	0.078	36.551	1.349	33.049	165850.	63481.	56535.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.656
DECEMBER 85	43861.	0.330	0.300	0.126	0.090	37.177	1.227	32.778	263503.	110339.	79176.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.299
TOTAL	4204477.	0.330	0.230	0.078	0.083	35.308	1.176	35.146	1939001.	663309.	703657.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.277

LEDGER FOR FURNACE SLAG (NI CIRCUIT)	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CD	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 86	29816.	0.000	0.295	0.031	0.083	36.400	1.400	35.600	175914.	18486.	49495.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	26.189
FEBRUARY 86	30767.	0.000	0.282	0.029	0.072	36.900	1.400	33.800	173526.	17845.	44304.	
	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	27.514
MARCH 86	34051.	0.000	0.282	0.028	0.086	35.800	1.300	34.500	192048.	19069.	58568.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.002
TOTAL	94634.	0.000	0.286	0.029	0.081	36.347	1.364	34.619	541488.	55400.	152367.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	27.272

LEDGER FOR FURNACE SLAG (CU CIRCUIT)	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CD	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 86	10149.	0.000	0.411	0.352	0.117	40.500	0.900	29.500	83425.	71449.	23749.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	28.218
FEBRUARY 86	12813.	0.000	0.318	0.287	0.113	38.200	0.900	31.400	81491.	73547.	28957.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.781
MARCH 86	10368.	0.000	0.156	0.224	0.050	34.700	0.800	34.800	32348.	46449.	10368.	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	29.270
TOTAL	33330.	0.000	0.296	0.287	0.095	37.812	0.869	31.879	197264.	191445.	63074.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.762

LEDGER FOR FURNACE SLAG TOTAL	TOTAL WEIGHT INSOL	H2O CAO	NI MGO	CU AL2O3	CO AS	FE ZN	S PB	SIO2 CD	LBS NI C/SO4	LBS CU NA	LBS CO K	BAL
JANUARY 86	39965.	0.000	0.324	0.113	0.092	37.441	1.273	34.051	259339.	89935.	73244.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	26.704
FEBRUARY 86	43580.	0.000	0.293	0.185	0.084	37.282	1.253	33.094	255017.	91392.	73261.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	27.887
MARCH 86	44419.	0.000	0.253	0.074	0.078	35.543	1.183	34.570	224396.	65518.	68936.	
	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	28.298
TOTAL	127964.	0.000	0.289	0.096	0.084	36.728	1.235	33.905	738752.	246845.	215441.	
	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	27.660

APPENDIX C

INFORMATION SUPPLIED BY CANADA CEMENT LAFARGE LTD. COVERING THEIR WORK ON THE CEMENTITIOUS PROPERTIES OF NONFERROUS SLAGS

C1	Covering Letter (T.R. Walton, contact) of 1978.
C2 to C16	Inco Thompson Granulated Nickel Slag.
C17 to C22	HBMS Air Cooled Copper Slag.
C23 to C29	Falconbridge Granulated Nickel Slag.
C30 to C41	Inco Sudbury Air Cooled Nickel Slag.
C42 to C53	Mitsubishi Granulated Copper Slag (to simulate Kidd Creek smelter).
C54 to C60	BMS Granulated Lead Slag.

CANADA CEMENT LAFARGE LTD.
240 DUNCAN MILL ROAD, DON MILLS, ONTARIO M3B 3H4
ONTARIO REGION

November 2, 1978

Mr. J.E.Belford,
Manager of Mining,
Texasgulf Canada Ltd.,
P.O.Box 2002,
Timmins, Ontario
P4N 7K1

Dear Eric:

Enclosed are excerpts from reports on the pozzolanic qualities of Inco, Sudbury, Inco - Thompson, Hudson Bay Mining, Falconbridge and Texasgulf slag.

You will note that T.G. slag has good pozzolanic qualities i.e.: A.S.T.M. tests C-595 and C-618.

The uniaxial compressive tests done with T.G. slag and concrete sand gave best results with an 8% addition of slag (as that % replacement of sand) and 4% cement. As you will note, when we substituted Inco-Tailings for the concrete sand and with a 12% slag addition, the strengths increased substantially over the equivalent 12% slag and concrete sand.

It would appear then that a finer gradation of fines is required, than that available from concrete sand, with only 2-10% passing No. 100 sieve.

In my estimation, Eric, Texasgulf's slag should have good pozzolanic qualities based on the sample of slag that we tested (as received from Mitsubishi in November 1975).

Best Regards.

Yours very truly,

T.R.Walton,
Manager - Mining Services.

TRW/cs
encls.
cc- J.W. CADOTTE

FORM CA-200

CANADA CEMENT LAFARGE LTD.

April 27, 1979.

Mr. C.N. Goddard,
Assistant to the Manager of Mines,
Inco Metals Ltd.,
Manitoba Division,
Thompson, Manitoba
R8N 1P3

Re: Thompson Granulated Nickel Slag Test
Project 20786 - 365 Day Test Results

Dear Carl:

There has been no strength gain between the 224 day and 365 day test interval with Slag A. We have experienced a decrease in compressive strength over the same test interval with Slag B and this can be attributed to oxidation.

However, the results obtained with both Slag A and B are satisfactory and enlightening.

With the coarse ground Slag A (2800 Blaine), the highest percentage of strength development had occurred by 112 days. With the fine ground Slag B (5680 Blaine), the highest percentage of strength development have occurred by 56 days.

We look forward to seeing you during the week of June fourth.

Yours very truly,

T.R. Walton,
Manager - Mining Services.

TRW/gm

c.c. J.A. Hagemeister
Winnipeg Sales Office.

COPY

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: Inco - Thompson - Project 20786 Slag B Blaine 5,680 cm^2/gm

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	
Inco T-70	68	1:25	Std.	Plant 13	30	40	43	47	21	0% slag addition
					35	38	46	51	24	
					34	38	48	55	20	
					33	39	46	51	22	
Inco T-71	68	1:25	Std.	Plant 13	45	51	51	47	40	4% slag addition,- as a replacement of that percentage of tailings 96% tailings
					38	49	50	41	41	
					38	46	44	54	-	
					40	49	48	47	40	
Inco T-72	68	1:25	Std.	Plant 13	35	55	38	35	31	8% slag 92% tailings
					33	50	39	35	-	
					34	39	44	40	30	
					34	48	40	37	30	
Inco T-73	68	1:25	Std.	Plant 13	48	50	60	47	39	12% slag 88% tailings
					48	46	47	40	35	
					41	47	46	43	35	
					46	48	51	43	36	
Inco T-74	68	1:25	Std.	Plant 13	54		65	-	40	16% slag 84% tailings
					54	71	74	55	39	
					53	53	61	45	41	
					54	62	67	50	40	

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: Inco - Thompson - Project 20786 Slag A Blaine 2,820 cm^2/gm

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	
Inco T-75	68%	1 to 16 2/3	Std.	Plant 13	61 39 41 47	55 63 62 60	65 65 56 62	70 67 73 70	51 31 46 43	0% slag addition
Inco T-76	68%	1 to 16 2/3	Std.	Plant 13	64 69 59 64	88 88 113 96	113 97 103 104	101 105 84 97	90 97 105 97	4% slag addition - as a replacement of that percentage of tailings 96% tailings
Inco T-77	68%	1 to 16 2/3	Std.	Plant 13	82 83 68 78	101 125 123 116	158 155 170 161	164 128 143 145	138 148 156 147	8% slag 92% tailings
Inco T-78	68%	1 to 16 2/3	Std.	Plant 13	98 90 95 94	148 133 133 138	165 147 143 152	- 164 169 167	166 164 179 170	12% slag 88% tailings
Inco T-79	68%	1 to	Std.	Plant 13	108 102 103 104	180 134 133 149	160 146 146 151	153 174 146 158	162 163 146 159	16% slag 84% tailings

FORM GA-200 -

CANADA CEMENT LAFARGE LTD.

November 9, 1978

Mr. C.N.Goddard,
Assistant to the Manager of Mines,
Inco Metals Ltd.,
Manitoba Division,
Thompson, Manitoba
R8N 1P3

Dear Carl:

Re: Thompson Granulated Nickel Slag Test Project 20786
224 Day Test Results

There has been little compressive strength gain over the last 112 day interval with either slag , fineness and this was to be expected, from previous testing.

As mentioned in my letter of July 18, 1978, regarding the 112 day test results, the coarse ground slag, 2820 sq cm/gm Blaine, with 6% cement and 8% slag addition appears to be still the most economical choice re: grinding costs and compressive strengths obtainable.

We look forward to seeing you on November twenty-second and twenty-third.

Best regards.

Yours very truly,

T.R.Walton,
Manager - Mining Services

TRW/cs
ecl.

c.c. - Mr. J.A. Hagemeister.

COPY

FORM GA-200

CANADA CEMENT LAFARGE LTD.

July 18, 1978.

Mr. C. N. Goddard,
Assistant to the Manager of Mines,
Inco Metals Limited,
Manitoba Division,
Thompson, Manitoba,
R8N 1P3

Dear Carl:

Re: Thompson Granulated Nickel Slag Test
Project 20786
112 Day Test Results

The coarse ground slag, 2,820 Blaine, with 6% cement is showing a consistent, strength gain over the last three test intervals, with each of the four slag addition levels.

The fine ground slag, 5,680 Blaine, with 4% cement is obviously sadly deficient in activator for the increased amount of particle surface area in this test series.

Best regards,

/gm

T. R. Walton,
Manager - Mining Services.

c.c. J. A. Hagemeister

COPY

Inco-Thompson

Project 20786

Test No. T-80A Tailings Sieve Analysis

Sieve No.	% Retained
70	16.1
100	24.2
140	24.2
200	17.1
325	12.3
-325	6.3
	100.0

Test No. T-80B Tube Percolation

mls./½ hr.	In/hr.	In/hr/in.	In/hr/in/in.
77.4	6.7	2.2	26.9

Test No. T-80C Density: 2.93 gm/cc.

Test No. T-80D 2" Cube Test

	Compressive Strength (psi)		
	14 day	28 day	90 day
C-T ratio 1:2.75	1920	2050	2300
H_2O (%) = 83.8	1920	2060	2280
Flow (%)= 104	1900	2020	2290
	1910	2040	2290
MPa =	13.2	14.1	15.8

Test No. T-81A Chemical Analysis

Compound	Slag A	Slag B
SiO_2	38.30	37.52
Al_2O_3	6.64	7.10
Fe_2O_3	6.92	5.42
FeO	33.49	34.77
CaO	2.59	2.54
MgO	4.88	4.86
Na_2O	1.19	1.15
K_2O	1.63	1.63
S	0.99	1.01
Loss	+3.91	+3.60
Total	96.63	96.00

Test No. T-81B

Density: 3.29 g/cc. 3.30 g/cc.

Test No. T-81C

Blaine: 2,820 cm^2/gm. 5,680 cm^2/gm.

Test No. T-81D

Glass Count: 99-100%

Inco-Thompson

Project 20786

Test No. T-81E ASTM C-595, Pozzolanic Activity with Hydrated Lime

	Slag, Blaine	
	A	B
Water	44.6	44.1
Flow	110	107
Compressive Strength	836 psi	1044 psi

Test No. T-81F ASTM C-618 Pozzonalic Activity with Portland Cement

	Slag, Blaine	
	A	B
Blaine	2,220	5,630 - dble. grinding req'd.
Control:		
Water	44.0	44.0
Flow	108	108
Compressive Strength	6,753 psi	6,753 psi
Pozzolanic Activity Index	58.2%	80.3%
Test:		
Water	46.4	44.8
Flow	108	108
Compressive Strength	3,933 psi	5,420 psi

Test No. T-81G ASTM C-109, 100% Cement Substitution by Slag

	Slag, Blaine	
	A	B
Water	42.0	42.0
Flow	105	105
Compressive Strength:		
3 day	nil	nil
7 day	nil	nil
28 day	23 psi	65 psi

FORM GA-200

CANADA CEMENT LAFARGE LTD.

April 19th, 1978

Mr. C. N. Goddard,
Assistant to the Manager of Mines,
Inco Metals Limited,
Manitoba Division,
Thompson, Manitoba,
R8N 1P3.

Dear Carl:

Re: Thompson Granulated Nickel Slag
Tests Project 20786

The 28-day uniaxial compressive strength test results for the 2,820 and 5,680 cm^2/gm Blaine slags would indicate that the Thompson slag requires more activator than used in the early testing - Project 20634.

The coarse ground slag (2,820 Blaine) with 6% cement gave improved compressive strength development. Grinding the slag finer to 5,680 Blaine (compared to the previous fine grind of 4,420 Blaine) and with the same percentage of cement (4%), resulted in a modest increase in compressive strength.

Therefore, the Thompson slag requires an increased amount of activator to fully utilize its pozzolanic qualities.

Also, the sieve analysis of the classified tailings received for this second series of tests has an improved gradation over the tailings used in the first test. This has undoubtably contributed to the increase in the compressive strength.

Jim and I have planned a trip to Thompson and Flin Flon the week of June 5th, and look forward to meeting with you at that time.

Best Regards,

T. R. Walton,
Manager, Mining Services.

TRW/ik

cc A. Hagemeister, Winnipeg Sales.

COPY

May 4, 1977

Mr. C. N. Goddard
Assistant to the Manager of Mines
Inco Ltd.
Manitoba Division
Thompson, Manitoba R8N 1P3

Dear Carl:

Re: Inco-Thompson Granulated Nickel Slag Tests
Project No. 20634

Enclosed are the 365 dav uniaxial compressive strength test results for the 2,250 and 4,420 cm^2/gm. Blaine slags. These test results conclude Project 20634.

The test results would indicate that the ground, granulated slag requires more activator than provided by the 4% cement.

Jim and I plan a trip to Thompson before the end of August. What would you suggest, Carl, as a suitable time?

Best regards,

T. R. WALTON
TECHNICAL SALES - MINING

TRW/bm
encl.
cc: J. Hagemeister - Winnipeg
W. Smith

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: Inco-Thompson - Project 20634 Slag B-1,Blaine 2250 Granulated.

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	
Inco T-61	68	1:25	Std.	Plant 13	21	23	25	30	37	0% slag addition
					20	22	28	32	33	
					(15)	21	26	30	38	
					20	22	26	31	36	
Inco T-62	68	1:25	Std.	Plant 13	20	26	29	29	30	4% slag addition - as a replacement of that percentage of tailings 96% tailings
					21	29	29	30	32	
					21	29	31	30	37	
					21	28	30	30	33	
Inco T-63	68	1:25	Std.	Plant 13	18	31	32	30	31	8% slag 92% tailings
					19	30	36	28	30	
					22	31	34	32	33	
					20	31	34	30	31	
Inco T-64	68	1:25	Std.	Plant 13	23	26	36	28	28	12% slag 88% tailings
					20	28	35	30	30	
					20	28	32	29	31	
					21	27	34	29	30	

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: Inco-Thompson Project 20634 Slag B-3, Blaine 4,420 Granulated.

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	
Inco T-61	68	1:25	Std.	Plant 13	21 20 (15)	23 22 21	25 28 26	30 32 30	37 33 38	0% slag addition
					20	22	26	31	36	
Inco T-65	68	1:25	Std.	Plant 13	27 22 21	31 34 34	40 40 39	33 31 39	30 32 30	4% slag addition - as per replacement of that percentage of tailings 96% tailings
					23	33	40	34	31	
Inco T-66	68	1:25	Std.	Plant 13	21 21 27	35 30 (24)	46 31 32	34 38 37	32 38 32	8% slag addition 92% tailings
					23	32	36	36	34	
Inco T-67	68	1:25	Std.	Plant 13	19 20 21	26 26 32	28 29 30	36 31 30	31 27 27	12% slag addition 88% tailings
					20	28	29	32	28	

Inco - Thompson
Project 20634

CYLINDER PERCOLATION DATA

Test No.	Cylinder No.	mls/½ hr. 28d	56d	112d	224d	365d	In/hr/in/in 28d	56d	112d	224d	365d
Inco T-61	16	1582	1170	790	776	695	103.0	76.3	51.5	50.6	45.3
	17	1000	772	271	259	138	65.2	50.3	17.7	16.9	9.0
Inco T-62	16	1032	823	548	372	306	67.3	56.7	35.7	24.2	20.0
	17	563	411	203	103	67	36.7	26.8	13.2	6.7	4.4
Inco T-63	16	555	342	275	165	154	36.2	22.3	17.9	10.8	10.0
	17	336	212	176	41	27	21.9	13.8	11.5	2.7	1.8
Inco T-64	16	522	490	228	(415)	(436)	34.0	31.9	14.9	(27.1)	28.4
	17	436	298	185	128	111	28.4	19.4	12.1	8.3	7.2
Inco T-65	16	490	310	202	170	(336)	31.9	20.2	13.2	11.1	21.9
	17	528	335	199	(252)	(305)	34.4	21.8	13.0	(16.4)	19.9
Inco T-66	16	369	289	165	(313)	(342)	24.1	18.8	10.8	(20.4)	22.3
	17	414	310	207	143	148	27.0	20.2	13.5	9.3	9.6
Inco T-67	16	295	134	108	(173)	(571)	19.2	8.7	7.0	(11.3)	37.2
	17	445	346	237	177	123	29.0	22.6	15.5	11.5	8.0

November 30, 1976

Mr. C.N. Goddard
Assistant to the Manager of Mines
Inco Limited
Manitoba Division
Thompson, Manitoba
R8N 1P3

Dear Carl,

Re: Inco-Thompson Granulated Nickel Slag Tests
Project No. 20634

Enclosed is the 224 day uniaxial compressive strength test results for the 2,250 and 4,420 cm^2/gm Blaine slags.

The mortar cube strengths at 14, 28 and 90 days are low and this can be contributed to the coarseness of the tailings. This certainly had some bearing on the low strength development of the cement - slag - tailing blends.

The motar cubes are cast from 1 part cement and 2.75 parts tailings. This is the ASTM C-109 mortar cube test but replacing the Ottawa silica sand with tailings simply to determine the compatibility with cement. Otherwise there is no practical use of this test to backfill application.

The results of this project have not been a total loss and it would be interesting to test a finer ground slag of plus 5,000 Blaine and a tailing product with an improved distribution of fines.

Best regards,

Yours very truly,

T.R. Walton
Technical Sales - Mining

Encl.

cc: J. Hagemeister - Winnipeg
W.A. Smith

Inco-Thompson

Project 20634

TEST NO. T-68A Tailings Sieve Analysis

Sieve No.	% Retained
70	44.6
100	27.0
140	15.7
200	6.8
325	3.9
-325	2.0
Total	100.0

TEST NO. T-68B Tube Percolation

mls/½ hr. In/hr In/hr/in In/hr/in/hr

TEST NO. T-68C Density: 2.82 gm/cc.

TEST NO. T-68D Bulk Density: dry, lb/cu.ft.

Inco T - 61	Inco T-62	Inco T-63	Inco T-64	Inco T-65	Inco T-66	Inco T-67
89.7	89.2	90.0	89.5	90.0	89.4	92.0

TEST No. T-69A Chemical Analysis:Granulated Slag

Compound	Slag B-1%	Slag B-3%
SiO_2	32.60	29.88
Al_2O_3) P_2O_5) TiO_2)	11.64	14.08
Fe_2O_3	7.81	5.92
FeO	39.47	38.04
CaO	2.78	2.74
MgO	4.87	5.42
Na_2O	1.00	1.06
K_2O	1.52	1.58
S(total)	0.92	1.20
loss	(+2.64)	(+3.48)
Total	102.61	99.92

TEST NO. T-69B Density: 3.35 3.35

TEST NO. T-69C Blaine cm^2/gm 2,250 4,420

TEST NO. T-69D Glass Count: Both samples were highly glassy. Glass count estimated to be more than 99%.

Inco Thompson

Project 20634

Tailings Data

TEST NO. T-68E 2 in. cube strength

C:T = 1:2.75

Compressive Strength, psi

14day	28day	90day
2000	2250	2520
2000	2220	2450
2040	2320	2500
2010	2260	2490

Slag Data

TEST NO. 69E Cube Strength

ASTM-C-109 modified - total amount of cement was replaced by slag. Both slags did not set.

TEST NO. 69F Pozzolanic Activity with Hydrated Lime : ASTM C-595.

Minimum Required	Slag B-1	Slag B-3
= 800# psi at 7 days	777	998

TEST NO. 69G Pozzolanic Activity with Normal Portland Cement+ASTM C-618

Minimum Required	Slag B-1	Slag B-3
85% of control at 28 days		
Control = 4,780 psi	2,980 psi	3,970 psi
Pozzolanic Activity Index	62.3%	83.3%

FORM GA-200

CANADA CEMENT LAFARGE LTD.

April 26, 1979

Mr. L. Nilsen,
Manager of Mining,
Hudson Bay Mining & Smelting Co. Ltd.,
P.O. Box 1500,
Flin Flon, Manitoba,
R8A 1N9

Re: H.B.M. & S. Air Cooled Slag - Tailings - Testing
Project 20819

Dear Lloyd:

Enclosed are the 224 day uniaxial compressive strength results on the 3,000 and 4,000 Blain slag - cement - tailings material.

As expected, the higher percentage additions of ground slag (16%) are showing a modest strength development.

As the test data reveals, by 56 days the test cylinders have obtained a high percentage of the expected strength gain - at all slag addition levels. There is also a decrease in the void ratio with the increasing amount of ground slag added, which also improves the uniaxial compressive strength.

Jack Falk and I will be in Flin Flon, sometime during the week of June 4th and will see you at that time.

Yours very truly,

T. R. Walton,
Manager - Mining Services.

TRW/gm

c.c. J.A. Hagemeister, Winn.Sales
W.A.Tindall,Purchasing Agent, H.B.M.& S.

COPY

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: H.B.M & S - Flin Flon Project 20819 Slag A Blaine 3,000 cm^2/gm

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	Flin Flon Tailings
HBM & S-21	68%	1:25	Std.	Plant 13	45 43 40	50 38 43	42 40 49	46 55 33		0% slag addition
					43	44	44	45		
HBM & S-22	68%	1:25	Std.	Plant 13	2.0 3.0 3.0	1.4 1.6 1.5	2.0 3.0 3.0	7.0 5.0 6.0		4% slag addition - as a replacement of that percentage of tailings
					3.0	1.5	3.0	6.0		96% tailings
HBM & S-23	68%	1:25	Std.	Plant 13	7.0 8.0 7.0	9.7 9.7 3.7	24 28	16 41 12		8% slag 92% tailings
					7.0	7.7	26	23		
HBM & S-24	68%	1:25	Std.	Plant 13	7.0 7.0 9.0	14.0 12.0 13.0	22 23	13 13 21		12% slag 88% tailings
					8.0	13	22	16		
HBM & S-25	68%	1:25	Std.	Plant 13	66 59 59	95 89 85	69 89 130	136 113 107		16% slag 84% tailings
					61	90	96	119		

C18

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: H.B.M. & S. - Flin Flon Project 20819 Slag B Blaine 4000 cm^2/gm

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST(DAYS)					SPECIAL CONDITIONS
					28	56	112	224	365	Snow Lake Tailings
HBM&S-27	68%	1:25	Std.	Plant 13	20 20 -	15 19 16	14 17 15	15 14 -		0% slag addition
					20	17	15	14		
HBM&S-28	68%	1:25	Std.	Plant 13	24 25 32	21 22 23	20 21	13 18 20		4% slag addition - as a replacement of that percentage of tailings
					27	22	20	17		96% tailings
HBM&S-29	68%	1:25	Std.	Plant 13	44 54 52	60 56 50	66 54 54	60 52 -		8% slag 92% tailings
					50	55	58	56		
HBM&S-30	68%	1:25	Std.	Plant 13	56 52 53	65 64 62	72 73 56	113 49 59		12% slag 88% tailings
					54	64	67	74		
HBM&S-31	68%	1:25	Std.	Plant 13	78 87 79	125 126 113	161 145 156	168 184 -		16% slag 84% tailings
					81	121	154	176		

C19

FORM GA-200

CANADA CEMENT LAFARGE LTD.

October 31, 1978

Mr. L.R.Nilsen,
Manager of Mining,
Hudson Bay Mining and Smelting Co. Ltd.,
P.O.Box 1500
Flin Flon, Manitoba
R8A 1N9

Dear Lloyd:

Re: H.B.M.&S Air cooled slag-tailings testing
Project 20819

Enclosed are the 112 day uniaxial compressive strength results on the 3,000 and 4,000 Blaine slag-cement-tailings material.

The two slags (the 3,000 and 4,000 Blaine) show continuing strength gain at all addition levels.

Bob Cotsworth and I look forward to seeing you November the twenty-first.

Best Regards,

TRW/cs
encls.

T.R.Walton,
Manager-Mining Services

c.c. J.A.Hagemeister.

COPY

HBM & S Flin Flon
Project 20819
Test No. 26 D

SLAG CHEMICAL ANALYSIS

	SLAG A 3,000 BLAINE	SLAG B 4,000 BLAINE
SiO_2	38.36	38.24
Al_2O_3) TiO_2) P_2O_5)	6.60 (4.98) Corrected Oct 16/73	6.53
Fe_2O_3	4.58 (6.20)	4.49
FeO	39.90	39.18
CaO	1.38	1.38
MgO	3.17	3.23
Na_2O	0.66	0.68
K_2O	0.56	0.59
Total Sulphur	0.86	0.83
Loss @ 1050°C	(+4.47)	(+3.99)
Total	96.07	95.15

Test No. 26 E

ASTM-C-109 - Cube strength - total amount of cement was replaced by slag. Both slags did not set.

Test No. 26 F

ASTM-C-595 - Pozzolanic Activity with Hydrated Lime

Minimum Reg'd	Slag A (3,000 Blaine)	Slag B (4,000 Blaine)
800 psi at 7 days	570 psi	230 psi

Test No. 26 G

ASTM-C-618 - Pozzolanic Activity with Normal Portland Cement

Minimum Reg'd 85% of control at 28 days	Slag A (3,000 Blaine)	Slag B (4,000 Blaine)
control 5,227 psi	4,547 psi	4,810 psi
Pozzolanic Activity Index		
100%	87%	92%

HBM & S - Flin Flon
Project 20819

Test No. 26A — 2 in. cube test Snow Lake Tailings

Compressive Strength (psi)

Cement - Tailing Ration	14 days	28 days	90 days
1:2.75			
Density	2550	3030	3490
3.47g/cc	2440	3060	3420
	2500	3040	3500
	2500	3040	3470

Test No. 26 B — 2 in. cube test Flin Flon Tailings

Compressive Strength (psi)

Cement - Tailing Ratio	14 days	28 days	90 days
1:2.75			
Density	2760	3110	3770
3.40 g/cc	2720	3100	3730
	2710	3080	3680
	2730	3100	3730

Test No. 26 C — Sieve Analysis

Flin Flon Tailings			Snow Lake Tailings		
Sieve	% Retained	% Passing	Sieve	% Retained	% Passing
# 70	10.5	89.5	# 70	11.5	88.5
100	19.3	70.2	100	14.7	73.8
140	20.4	49.8	140	17.8	56.0
200	19.5	30.3	200	20.8	35.2
325	17.9	12.4	325	21.3	13.9
-325	12.4	0	-325	13.9	0

PROJECT 20607C February 2, 1977

Falconbridge electric furnace granulated slag, sample GSL-31B received Nov. 30, 1976.

Density	3.49 gm/cc
Blaine	2840 cm^2/gm
Passing 325 sieve	87.1%

Tested as follows -

Pozzolanic Activity with Lime, ASTM C-595

7 days 894 psi

Pozzolanic Activity with Portland Cement ASTM C-618

Control Cement (Market Sample Dec. 76)
28 days 5,060 psi

Test with slag at 28 days 3,210 psi

Pozzolanic Activity Index $\frac{3,210}{5,060} = 63.4\%$

PROJECT 20607A

FALCONBRIDGE - 287 SLAG DATA

TEST 287A - Chemical Analysis

SiO_2	28.96%
Al_2O_3	7.57
Fe_2O_3	3.86
FeO	45.22
CaO	5.14
MgO	3.38
Na_2O	1.03
K_2O	0.87
S	1.79
Loss*	2.14
Total	99.96

* Calculated from oxidation of FeO to Fe_2O_3 minus experimental gain in ignited weight.

Test 287B - Density: 3.94 gm./c.c.

Test 287C - Blaine: 3040 $cm^2/gm.$

Test 287D - Fineness: (passing 325 mesh) 80.2%

Test 287E - Cube Strength:

ASTM C109 modified. All of the cement required in this specification was replaced by the slag. The cubes did not set.

Test 287F - Pozzolanic Activity with Hydrated Lime ASTM-595

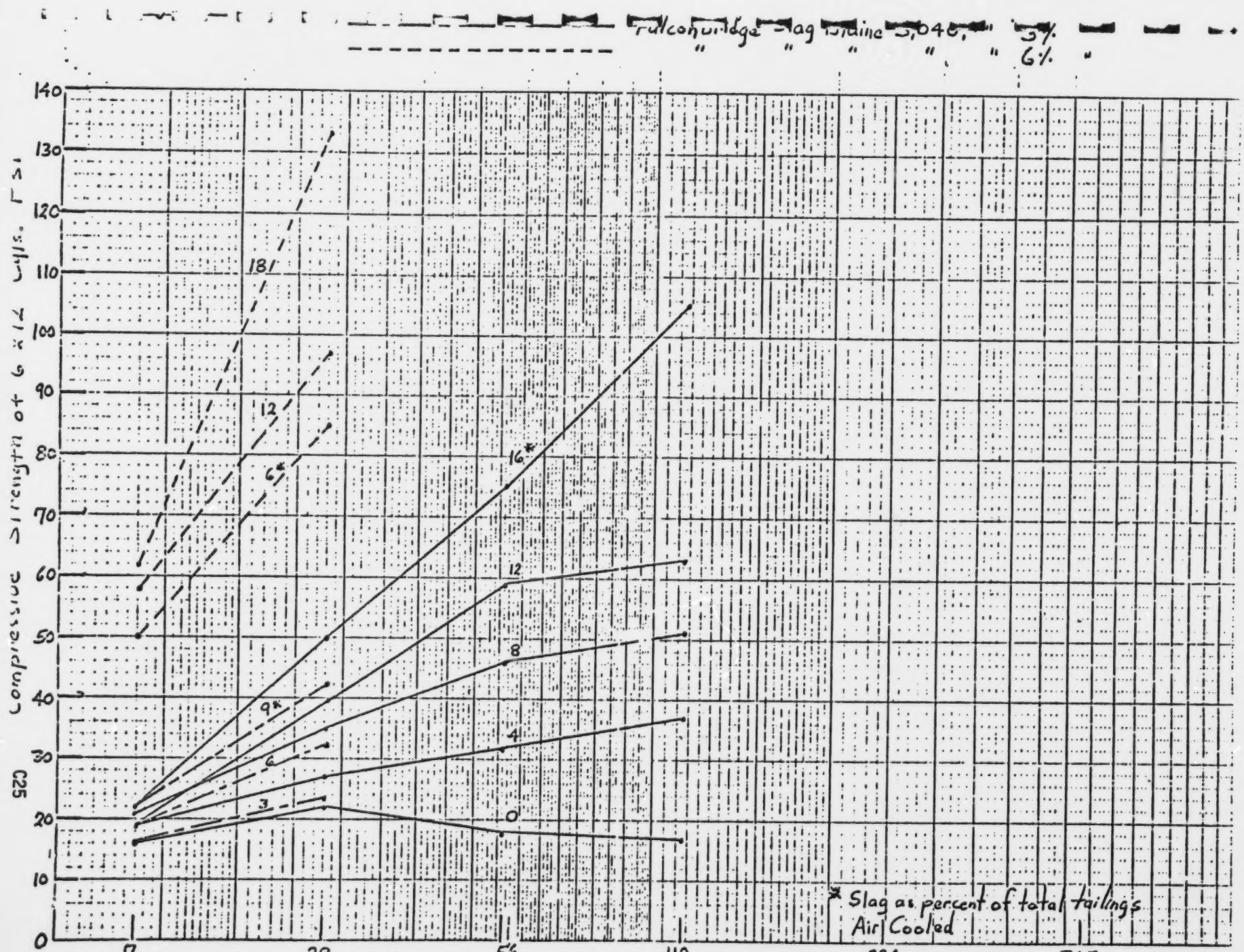
Water (%)	42.0
Flow (%)	105

Compressive Strength (7 days) 281 psi.

Test 287G - Pozzolanic Activity with Portland Cement ASTM C618

Control Test (28 days)		Slag Test (28 days)	
Water (%)	50.0	Water (%)	40.4
Flow (%)	107	Flow (%)	109
Comp. Str.	5140 psi	Comp. Str.	2850 psi

Pozzolanic Activity Index $\frac{2,850}{5,140} = 55.4\%$


Falconbridge Slag Blaine 3,040, 3%
" " " " " 6% "
Compressive Strength of 6 x 12 Cyls. PSI
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
181
12
6*
16*
12
8
9*
6
4
3
0
7
28
56
112
224
365
* Slag as percent of total tailings
Air Cooled

PROJECT 20607A

FALCONBRIDGE - 286 TAILINGS DATA

TEST 286A - Sieve Analysis

Sieve No.	% Retained
70	13.5
100	14.0
140	16.0
200	14.0
325	15.8
-325	26.7
Total	100.0

TEST 286B - Tube Percolation

mls./½ hr.	In./hr.	In/hr./in.	In./hr./in./in.
47	4.1	1.4	16.8

TEST 286C - Density: 2.92 gm./cc.

TEST 286D - Bulk Density: dry, lb./cu. ft.

F-278	F-279	F-280	F-281	F-282	F-283	F-284	F-285
92.7	95.9	96.0	98.4	93.3	98.0	101.5	104.6

TEST 286E - 2 Inch Cube Strength

C-T Ratio = 1:2.75

Water (%) = 83.8

Flow (%) = 112

Compressive Strength, psi		
14 days	28 days	90 days
2560	2,990	
2590	2,970	
2570	2,960	
2570	2,970	

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

PROJECT 20607A

TESTS CARRIED OUT FOR: FALCONBRIDGE NICKEL MINES LTD./AIR COOLED SLAG/SLAG BLAINE 3,040 cm^2/gm.

TEST NO.	PULP DENSITY %	% CEMENT	% SLAG	% TAILINGS	AGE OF TEST (DAYS) 7	28	56	112	224	365	SPECIAL CONDITIONS
F-278	70	1.4	0	98.6	7	8	10				Tailings received Oct. 28/76. Slag received Dec. 20/76. Plant 9 cement rec. Nov. 16/76
					6	9	9				
						9	9				
						9	9				
F-279	70	3.0	3.0	94.0	16	22					
					16	24					
					16	23					
					16	23					
F-280	70	3.0	6.0	91.0	19	34					
					18	32					
					19	31					
					19	32					
F-281	70	3.0	9.0	88.0	21	42					
					22	41					
					22	43					
					22	42					
F-282	70	2.8	0	97.2	13	17	21				
					11	17	21				
					11	18	21				
					11	17	21				
F-283	70	6.0	6.0	88.0	52	87					
					50	82					
					48	85					
					50	85					
F-284	70	6.0	12.0	82.0	57	97					
					56	93					
					6	100					
					58	97					
F-285	70	6.0	18.0	76.0	60	139					
					63	129					
					61	131					
					62	133					

C27

CANADA CEMENT LAFARGE LTD.

CEMENT TAILINGS STUDIES

PROJECT 20607A
TESTS CARRIED OUT FOR: FALCONBRIDGE NICKEL MINES

TEST NO.

CYLINDER PERCOLATION DATA mls./½ hr.

TEST NO.	CYL. NO.	7d	14d	28d	56d	112d	224d
F-278	16	237	190	128	95		
F-279	16	275	164	116			
	17	200	88	66			
F-280	16	128	49	41			
	17	207	112	99			
F-281	16	83	55	46			
	17	23	29	18			
F-282	16	302	270	248	195		
	17	217	178	149	102		
F-283	16	63	19	18			
	17	52	20	12			
F-284	16	121		8			
	17	83		5			
F-285	16	43		13			
	17	97		14			

CANADA CEMENT LAFARGE LTD.

CEMENT TAILINGS STUDIES

PROJECT 20607A
TESTS CARRIED OUT FOR: FALCONBRIDGE NICKEL MINES

TEST NO.

CYLINDER PERCOLATION DATA

In./hr./in./in.

TEST NO.	CYL. NO.	7d	14d	28d	56d	112d	224d
F-278	16	15.5	12.4	8.3	6.2		
F-279	16	17.9	10.7	7.6			
	17	13.0	5.7	4.3			
F-280	16	8.3	3.2	2.7			
	17	13.5	7.3	6.5			
F-281	16	5.4	3.6	3.0			
	17	1.5	1.9	1.2			
F-282	16	19.7	17.6	16.2	12.7		
	17	14.1	11.6	9.7	6.6		
F-283	16	4.1	1.2	1.2			
	17	3.4	1.3	0.8			
F-284	16	7.9		0.5			
	17	5.4		0.3			
F-285	16	2.8		0.8			
	17	6.3		0.9			

March 1, 1977

Mr. C. Barsotti
Assistant to the
Chief Mines Engineer
Inco Ltd.
Copper Cliff, Ontario
P0M 1N0

Dear Claudio:

Re: Inco - Sudbury Air Cooled Nickel
Reverb Slag Tests
Project - 20636-A

The uniaxial compressive strength of test number Inco-300 cement-tailings ratio of 1:8, no slag addition, broke below the expected strength. This lower strength, 33 psi, can be attributed to sulphide expansion, in the top half of the 6" x 12" cylinder, caused by oxidation of the tailings. The cylinders (112 days) were cut in half and tested again in compression. The strengths were in the 90 psi level - still lower than expected but acceptable.

Enclosed are the 7 and 28 day tests on the Falconbridge air cooled slag. A small sample of this slag was ground to 4,000 cm^2/gm. Blaine, at your request, to be compared with the Inco air cooled slag results. All Falconbridge air cooled slag tests use a slag Blaine of 3,000 cm^2/gm and the results of those tests are also enclosed.

You will notice that the results using 4% cement, 8% slag, at 4,000 Blaine, produce strengths approximately 30% higher than the 3% cement, 9% slag at 3,000 Blaine.

Also the pozzolanic activity of the Falconbridge slag is lower, using the two ASTM tests C-595 and C-618 - this can be attributed to the chemical composition. However, this lower pozzolanic activity does not manifest itself in the uniaxial compressive strength tests.

Best regards,

T. R. WALTON
TECHNICAL SALES -
MINING

TRW/bm

encl.

cc: A. W. Cadotte
J. H. Holtby, Supt. Purchasing
W. A. Smith

CANADA CEMENT LAFARGE LTD.

CEMENT-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: INCO - SUDBURY PROJECT 20636-A SLAG BLAINE - 3,700 cm^2/gm (2nd shipment)

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST (DAYS) 7	28	56	112	365	SPECIAL CONDITIONS
Inco 293	68	1:25	Std.	Plant 9	16 16 16	21 22 23	20 19 16	17 18 17		0% slag addition 100% tailings
					16	22	18	17		
Inco 298	68	1:25	Std.	Plant 9	44 (29) 48	73 (54) 80	91 88 (72)	117 70 61		16% slag addition 84% tailings
					46	77	90	83		
Inco 299	68	1:25	Std.	Plant 9	44 42 50	98 90 94	100 122 (67)	124 115 109		20% slag addition 80% tailings
					45	94	111	116		
Inco 300	68	1:8	Std.	Plant 9	27 28 28	51 50 67	61 64 56	30 32 36		0% slag addition 100% tailings * Top ½ cylinders undergone expansion due tailings oxidation
					28	56	60	33*		
								93 91 92**		Inco 300 ** Bottom ½ of cylinders re-tested.

C32

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-TAILINGS CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: INCO-SUDBURY, PROJECT 20636A

Falconbridge Air Cooled Slag - 4,010 Blaine
Falconbridge Tailings

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST (DAYS) 7	28	56	112	224	365	SPECIAL CONDITIONS
Inco 303	70	1:25	Std.	Plant 9	30	54	66	75			8% slag addition 92% tailings
					29	53	67	74			
					30	54	69	70			
					29	54	67	73			

C33

PROJECT 20636A

INCO - TEST 304: Falconbridge Air Cooled Slag Data

304A: Chemical Analysis

SiO_2	28.96%
Al_2O_3	7.57
Fe_2O_3	3.86
FeO	45.22
CaO	5.14
MgO	3.38
Na_2O	1.03
K_2O	0.87
S	1.79
Loss*	2.14
Total	99.96

*Calculated from oxidation of FeO to Fe_2O_3 minus experimental gain in ignited weight.

304B: Density 3.94 gm/c.c.

304C: Blaine 4010 cm^2/gm.

304D: Fineness 87.2% passing 325 mesh

304E: Cube strength - ASTM C109 modified, all of the cement required in this specification was replaced by slag. The cubes did not set.

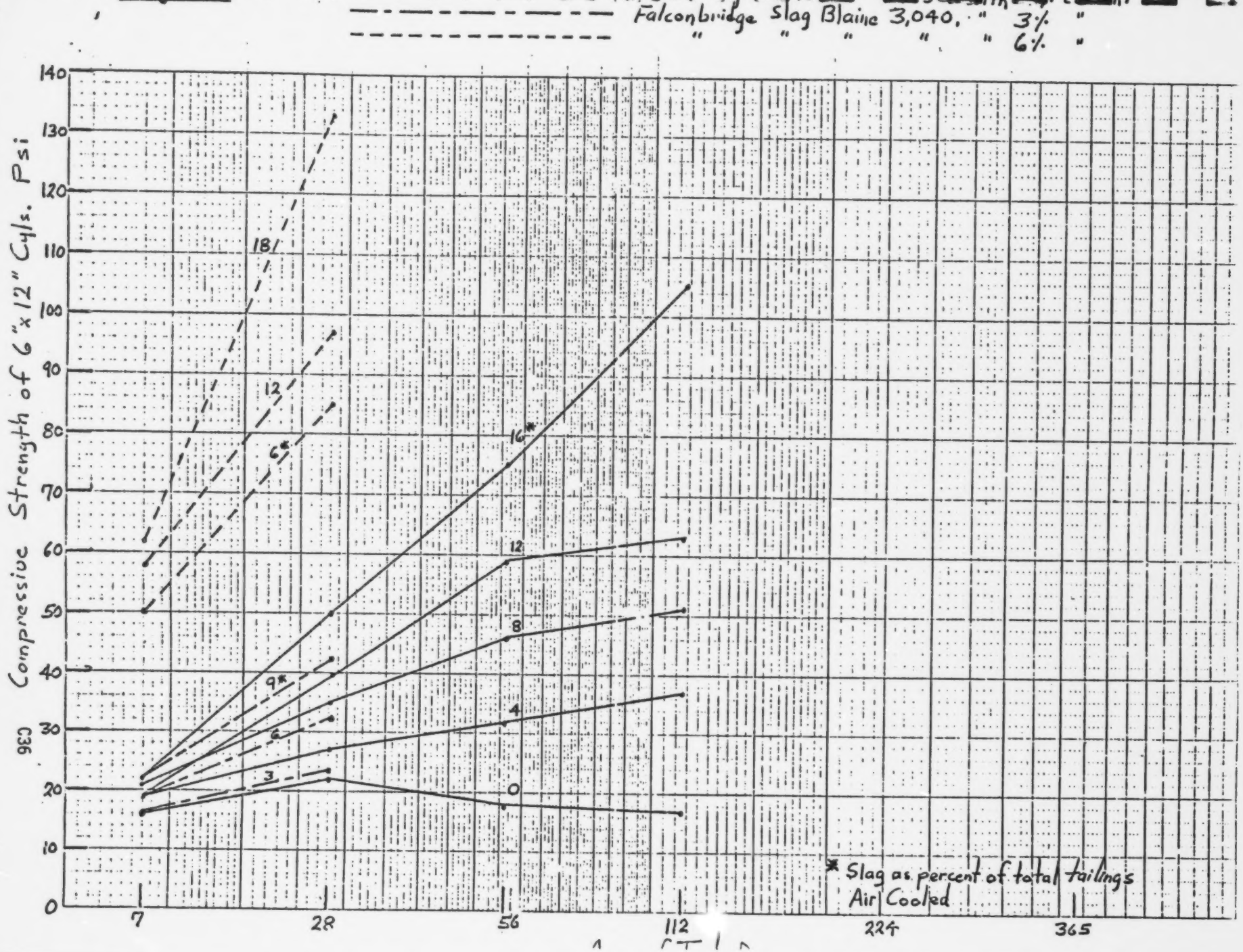
304F: Pozzolanic Activity with Hydrated Lime ASTM - C595

Water (%)	45.3
Flow (%)	102
Comp. Str. (7 days)	224 psi

304G: Pozzolanic Activity with Portland Cement
ASTM C-618

	Control Test	Slag Test
Water (%)	50.0	46.0
Flow (%)	107	104
Comp. Str.(28 days)	5,140 psi	3,240 psi

Pozzolanic Activity Index $\frac{3,240}{5,140}$ = 63.0%


Falconbridge Slag Blaine 3,040, " 3% "
" " " " " 6% "
Compressive Strength of 6"x12" Cyls. Psi
C36
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
18
12
6*
16*
12
8
4
9*
6
3
0
7
28
56
112
224
365
* Slag as percent of total tailings
Air Cooled

May 28, 1976.

Mr. C.Barsotti,
Assistant to the Chief Mines Engineer,
Inco Canada Ltd.
Ontario Division,
Copper Cliff, Ontario
P0M 1N0.

Dear Claudio,

Re: Inco-Sudbury Air Cooled Nickel Reverb.
Slag Tests - Project 20638.

The results of the uniaxial compressive tests at 7 and 28 days are encouraging.

Seemingly, the glass count has little bearing on the pozzolanic quality of this slag - a glass count on this air cooled lump slag will be available at a later date. If the slag is finely ground and,most important,if the chemical composition meets or closely meets the ASTM C-618 specification for pozzolanic material, beneficial results can be expected.

You will note that the surface area determined by Ontario Research Foundation was 4,140 Blaine, the average of 7 samples and a recheck on the blended sample taken by our laboratory found the Blaine to be 3,730.

This slag does not meet all the requirements laid down in the specification but it does meet the pozzolanic activity index with lime at 7 days (C-595) and with portland cement at 28 days (C-618).

The chemical requirements of ASTM C-618 state that the SiO_2 plus Al_2O_3 plus Fe_2O_3 must be a minimum of 70% - the Inco Sudbury slag is 58.8% - higher than several other slags tested recently.

It would appear that the chemical composition of the slag is most important and of course, the uniformity of the chemical composition must be maintained for consistent results.

The 56 day uniaxial compressive test results will be available in early June.

Best regards.

Yours very truly,

TRW/jv.
Encl.

T.R.Walton, P.Eng.
Technical Sales - Mining.

Note: The glass count is 82.5%.

c.c.: A.W.Cadotte
W.A.Smith.

Inco - Sudbury

Project 20636

TEST NO. 298A - Tailings Sieve Analysis

Sieve No.	% Retained
70	25.2
100	20.4
140	19.4
200	13.6
325	11.2
- 325	10.2
	100

TEST NO. 298B - Tube Percolation

mls/½ hr	In/hr	In/hr/in	In/hr/in/in

TEST NO. 298C - Density: 3.07 gm/cm

TEST NO. 298D - Bulk Density: dry, lb/cu.ft.

Inco 293	Inco 294	Inco 295	Inco 296	Inco 297
104.0	105.5	--	106.3	106.6
100.0	103.7	104.7	102.0	105.5
100.0	104.0	104.6	104.1	105.7
104.4	--	106.4	103.0	105.6
102.1	104.4	105.2	103.9	105.9

C38

TEST NO. 299A - Chemical Analysis Nickel Reverb.Slag

Compound	%	Comment
SiO_2	34.08	difficulty encountere in obtaining pure SiO
Al_2O_3) P_2O5) TiO2)	14.52	
Fe_2O_3	10.20	
FeO	38.40	
CaO	0.30	
MgO	17.60	
Na_2O	1.04	
K_2O	0.72	
Total S	1.59	
Loss	(+3.52)	
Total	118.45	

TEST NO. 299B - Density: 3.63 gm/cm

TEST NO. 299C - Blaine: 3730 cm^2/gm.

Slag Data Continued

TEST NO. 299D

ASTM C-595 Pozzolanic Activity Test Section 7.16.5

- To determine the activity of the pozzolan constituent with hydrated lime at 7 days
- Pozzolanic Strength, min. psi = 800 psi required
  " " of slag sample = 964 psi

TEST No. 299E

ASTM C-618 Pozzolanic Activity Index with Portland Cement Section 5.1.4

- Pozzolanic activity index with portland cement at 28 days, min. percent of control = 85%
- Control: Plant 9 Normal Portland = 5,390 psi
  Test: Slag Sample = 4,740 psi
  Pozzolanic Activity Index = 87.9%

ONTARIO RESEARCH FOUNDATION

SHERIDAN PARK, MISSISSAUGA, ONTARIO, CANADA, L5K 1R3 PHONE (416) 822-4111 OR 279-9771 * TELEX 06 982311

March 8, 1976

Mr. T.R. Walton
Technical Sales - Mining
Ontario Region
Canada Cement LaFarge Ltd.
240 Duncan Mill Road
Don Mills, Ontario
M3B 3H4

Dear Mr. Walton:

Re: C.C.L. Project 20636
Inco Slag Grinding
Our Investigation No. P-75416

A sample of Inco slag provided to us was ground to an average particle size of 4140 Blaine. The total ground product of 400 pounds was shipped to your Belleville laboratories on March 5, 1976.

The material was received in lump form and was crushed in a jaw crusher, then ground in 60 pound batches in a Hardinge conical ball mill (2 ft. x 8 inch) using a ball charge of 400 pounds of 1 inch - 1-1/2 inch steel balls. The grinding times and product particle sizes are shown in the following table. Blaine measurements were based on a measured specific gravity of 3.53.

THIS REPORT RELATES ONLY TO THE PARTICULAR INSTRUMENT, MATERIAL, OR OTHER SUBJECT REFERRED TO IN IT. NO REPRESENTATION IS MADE THAT SIMILAR ARTICLES WILL BE OF LIKE QUALITY. WITHOUT THE PRIOR WRITTEN CONSENT OF THE ONTARIO RESEARCH FOUNDATION, NO PUBLICATION IN WHOLE OR IN PART OF THE TEXT OR SUBSTANCE OF THIS REPORT SHALL BE MADE, NOR SHALL THE NAME OF THE ONTARIO RESEARCH FOUNDATION BE USED IN ANY WAY IN CONNECTION WITH THE SALE, OFFERING OR ADVERTISING OF ANY ARTICLE OR PRODUCT. ANY TESTING, INSPECTION OR INVESTIGATION OF THE INSTRUMENTS, MATERIALS OR OTHER SUBJECTS PERFORMED BY ONTARIO RESEARCH FOUNDATION WILL BE CONDUCTED IN ACCORDANCE WITH THE BEST TECHNICAL STANDARDS BY THE ON C40 EARCH FOUNDATION BUT NEITHER IT NOR ITS EMPLOYEES SHALL BE RESPONSIBLE FOR ANY LOSS OR DAMAGE RESULTING DIRECTLY OR INDIRECTLY FROM ANY DEFAULT. -OMISSION

Grind	Charge Wt. (Slag)	Grinding Time	Blaine Reading (cm^2/g)	
1	60 pounds	2 hr. - 30 min.	4373	
2	" "	2 hr. - 20 min.	4005	
3	" "	2 hr. - 20 min.	3905	
4	" "	2 hr. - 30 min.	4046	average 4140
5	" "	2 hr. - 30 min.	4025	
6	" "	2 hr. - 35 min.	4189	
7	40 pounds	2 hr.	4584	

The products from runs 1, 2, 3, 4 and half of run #7 were placed in a metal drum. Products from runs 5, 6 and half of run #7 were placed in a fiber drum and both drums were shipped to Canada Cement LaFarge (Belleville Laboratories).

Yours truly,

W.F. Fossen, P.Eng.
Associate Research Engineer
Department of Metallurgy

WFF:jc

December 3, 1978

Dr. T. Yu
Rock Mechanic's Research Engineer
Texasgulf Canada Ltd.
P.O. Box 2002
Timmins, Ontario
P4N 7K1

Dear Thiann,

Re: Mitsubishi Granulated Slag Tests
Project 205100

Enclosed are the 224 day laboratory results for the uniaxial compressive strength tests and cylinder percolation tests.

Within the test parameters used, the 12 percent slag replacement of alluvial sand appears to be the optimum addition level.

This report concludes this test project. One definite observation can be made -- the granulated slag is pozzolanic and the addition of this ground slag to portland cement would impart additional physical benefits.

Best regards,

Yours very truly,

T.R. Walton
Technical Sales - Mining

Encl.

cc: Mr. G.M.T. Marshall, Superintendent of Engineering & Technical Services) Texasgulf
Mr. D. Porteous, Chief Engineer) Canada Ltd.
Mr. J.V. MacDonnel, Purchasing Agent)
Mr. A.W. Cadotte)
Mr. W.A. Smith) C.C.L.

CANADA CEMENT LAFARGE LTD.

CEMENT-SLAG-ALLUVIAL SAND CYLINDER COMPRESSIVE STRENGTH RESULTS (P.S.I.)

TESTS CARRIED OUT FOR: Texasgulf Canada Ltd. Project 205100

TEST NO.	PULP DENSITY %	C-T RATIO	CURING COND.	CEMENT	AGE OF TEST (DAYS)					SPECIAL CONDITIONS Note One
					7	28	56	112	224	
TGS-36	70	1:25	Std.	Plant 9	9	14	17	12	11	0% Slag, Std. Concrete Sand
TGS-37					6	8.5	14	20	18	4% " " " "
TGS-38					9	19	18	21	20	8% " " " "
TGS-39					9	15	18	19	28	12% " " " "
TGS-40					7	11	18	13	20	16% " " " "
TGS-36A					22	50				12% Slag,Std.Classified Mine T. li
TGS 37A					11	19				0% " " " " "

Note One - 4, 8, 12 & 16 perce addition of slag, as a replacement of that percentage of alluvial sand.

C43

PROJECT 205100

CYLINDER STRENGTH DATA

Cement: Sand Ratio = 1 : 25

Pulp Density: 70%

Test No	Slag* %	Compressive Strength, psi 7d	28d	56d	112d	224d
TGS-36	0	-	-	-	-	-
		9	14	18	14	11
		9	14	16	11	11
		9	14	17	12	11
TGS-37	4	-	-	-	-	-
		6	8	(10)	22	19
		7	9	19	19	17
		6	8	19	20	18
TGS-38	8	13	17	-	-	-
		6	(11)	19	18	19
		8	22	17	24	20
		9	19	18	21	20
TGS-39	12	9	16	-	-	-
		11	(9)	19	14	25*
		7	14	17	24	30
		9	15	18	19	28
TGS-40	16	6	15	-	-	-
		7	9	(10)	14	24
		8	10	18	12	16
		7	11	18	13	20
TGS-36A**	0	11	19			
TGS-39A**	12	22	50			

* Percent replacement of sand
** Inco standard tailings used instead of sand

CANADA CEMENT LAFARGE LTD.

CEMENT TAILINGS STUDIES

TESTS CARRIED OUT FOR: Texasgulf Canada Ltd. Project 205100

TEST NO.

CYLINDER PERCOLATION DATA: In/hr./in./in

TEST NO.	CYL.NO.	7d	14d	28d	56d	112d	224d
TGS - 36	4	19.0	25.2	19.8	15.6	12.5	9.1
	7	39.9	33.0	28.2	21.5	14.0	11.1
TGS-37	4	43.9	46.8	41.4	34.2	30.0	23.0
	7	49.9	49.9	39.8	36.3	32.3	26.7
TGS-38	8	23.1	25.7	23.9	15.8	8.5	5.0
	11	21.3	21.6	12.8	9.3	7.8	6.8
	14	24.5	24.0	14.0	9.4	5.3	3.6
TGS-39	8	20.7	34.3	22.2	15.3	16.4	10.3
	11	15.8	15.4	10.9	9.0	7.1	6.9
	14	38.5	36.4	21.8	20.7	13.4	9.4
TGS-40	13	22.0	21.1	19.8	14.6	8.2	4.4
	14	24.6	25.8	23.3	18.8	13.4	11.5
	15	15.6	14.7	13.8	13.4	11.0	9.4

CANADA CEMENT LAFARGE LTD.

CEMENT TAILINGS STUDIES

TESTS CARRIED OUT FOR: Texasgulf Canada Ltd. Project 205100

TEST NO.

CYLINDER PERCOLATION DATA: mls/½ hr.

TEST NO.	CYL.NO.	7d	14d	28d	56d	112d	224d
TGS-36	4	292	386	304	239	191	140
	7	612	506	433	329	216	171
TGS-37	4	673	718	635	525	460	352
	7	765	765	611	556	495	410
TGS-38	8	354	394	367	242	130	76
	11	326	334	196	143	119	105
	14	376	368	214	144	82	55
TGS-39	8	318	526	340	235	252	158
	11	243	236	167	138	109	106
	14	590	558	334	318	205	144
TGS-40	13	337	324	304	224	126	67
	14	378	394	357	289	206	167
	15	240	225	212	205	169	144

January 21, 1976.

Dr. C.Yu,
Rock Mechanics Research Engineer,
Texasgulf Canada Ltd.,
P.O.Box 2002,
Timmins, Ont.
P4N 7K1.

Dear Chien,

Re: Mitsubishi Granulated Slag
Project No. 205100.

This letter will confirm the results of the pozzolanic activity test with cement ASTM C-618 that I gave you verbally last week.

a. Pozzolanic activity index ASTM - C 618

- with portland cement, at 28 days, control mix 5,110 psi
  test mix 3,850 psi

$$\text{therefore } \frac{3,850}{5,110} = 75.3\%.$$

the activity index for a class S pozzolan is a minimum of 85% of the control mix and for a class N pozzolan it is a minimum of 75%.

b. Pozzolanic activity with hydrated lime

- at 7 days - C-595 or C-618 is minimum of 800# psi.
- the Texasgulf slag material gave a 7 day strength of 1,000 psi.

Since none of the literature available in Canada or the U.S. mentions what pozzolanic class a metallurgical slag - nickel - copper - zinc or lead would fall under - it is my opinion that it would comply to the Class N Category.

However, this means very little as you are not in the market to sell your slag as a pozzolan.

cont.....

The results of the pozzolanic tests simply indicate that the Texasgulf granulated slag has pozzolanic qualities and can be used for that puspose.

The results of the 7 day uniaxial compressive strength tests will now be available the week of February the second.

Best regards.

T.R.Walton,
Technical Sales - Mining.

TRW/jv.

c.c.: G.M.T.Marshall,
J.VMacDonnell,
T.Dowe.

N.Anderson
W.A.Smith

ONTARIO RESEARCH FOUNDATION

SHERIDAN PARK, MISSISSAUGA, ONTARIO, CANADA, L5K 1B3 PHONE (416) 822-4111 OR 279-9771 • TELEX 06-982311

January 8, 1976

Mr. T.R. Walton
Technical Sales - Mining
Ontario Region
Canada Cement LaFarge Ltd.
240 Duncan Mill Road
Don Mills, Ontario
M3B 3H4

Dear Mr. Walton:

Re: C.C.L. Project 205100
Texas Gulf Slag Grinding
Our Investigation No. P-75416

The sample of Texas Gulf slag provided to us was ground to an average particle size of 3011 Blaine and provided a total ground product of 610 pounds which was shipped to your Belleville laboratories on December 12, 1975 via CN transport.

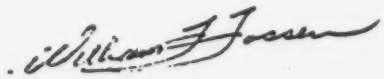
Initially, a 500 pound lot was ground in ten x 50 pound batches in a Hardinge conical ball mill (2" x 8") using a charge of 400 pounds of 1 to 1-1/2 inch steel balls. A grinding time of 2 hours was used for each batch. Control samples indicated particle sizes varying from 2830 to 3295 Blaine with an average of 3011 Blaine. These sizes were based on a specific gravity of 3.53 measured in our laboratory. This 500 pound lot of ground product was loaded into a 45 gallon drum for shipment.

Subsequently, the remaining slag was ground in two 55 pound batches for 2 hours each, bagged and placed in the 45 gallon drum with the original 500 pound lot. A sample of this latter product was measured to have a particle size of 3155 Blaine.

THIS REPORT RELATES ONLY TO THE PARTICULAR INSTRUMENT, MATERIAL, OR OTHER SUBJECT REFERRED TO IN IT. NO REPRESENTATION IS MADE THAT SIMILAR ARTICLES WILL BE OF LIKE QUALITY. WITHOUT THE PRIOR WRITTEN CONSENT OF THE ONTARIO RESEARCH FOUNDATION, NO PUBLICATION IN WHOLE OR IN PART OF THE TEXT OR SUBSTANCE OF THIS REPORT SHALL BE MADE, NOR SHALL THE NAME OF THE ONTARIO RESEARCH FOUNDATION BE USED IN ANY WAY IN CONNECTION WITH THE SALE, OFFERING OR ADVERTISING OF ANY ARTICLE OR PRODUCT. ANY TESTING, INSPECTION OR INVESTIGATION OF THE INSTRUMENTS, MATERIALS OR OTHER SUBJECTS PERFORMED BY ONTARIO RESEARCH FOUNDATION SHALL BE CONDUCTED IN ACCORDANCE WITH THE BEST TECHNICAL STANDARDS BY THE ONTARIO RESEARCH FOUNDATION BUT NEITHER IT NOR ITS EMPLOYEES SHALL BE RESPONSIBLE FOR ANY LOSS OR DAMAGE RESULTING DIRECTLY OR INDIRECTLY FROM ANY DEFAULT, OMISSION.

Small amounts of tramp oversize material may be present due to entrapment of particles under the lid of the ball mill. A subsequent screening operation would be required if this amount of oversize material is detrimental.

Yours truly,



W.F. Fossen, P.Eng.,
Associate Research Engineer,
Department of Metallurgy.

WFF:jc

Group A

December 11, 1975.

Mr. G.M.T.Marshall,
Superintendent of Engineering
and Technical Services,
Texasgulf Canada Ltd.,
P.O.Box 2002,
Timmins, Ont.
P4N 7K1.

Dear Merle,

Re: Mitsubishi: Granulated Slag, Project # 205100.

The glass content of the slag determined by light microscope with polarizing element is 94%. XRD (x-ray diffraction) revealed no crystalline material.

The moisture content, as received was 0.55%.

The Hardgrove Index (grindability) was 28. The lower the Hardgrove Index, the harder the material is to grind. Cement clinker runs about 45 to 70 on the Hardgrove Index.

The chemical analysis of the slag reveals the following composition:

SiO_2	-	34.64%
Al_2O_3) P_2O_5) TiO_2)	=	5.13%
Fe_2O_3	-	8.34%
FeO	-	41.18%
CaO	-	7.63%
MgO	-	1.97%
Na_2O	-	0.26%
K_2O	-	0.58%
S(total)	-	0.63%
Loss (Gain)	-	+(3.80) not included in total
Total		100.36%

cont.....

"Various formulae have been evolved, from experience and from tests on the strength of granulated slag mixes, for the composition desirable in the slag. In the absence of any quantitative theory of the relation between the activity and composition of the granulated slag, such formulae cannot be more than useful working rules, but such rules are obviously necessary as a guide in production" ---The Chemistry of Cement and Concrete --- Third Edition, F.M.Lea.

The hydraulic moduli we use is the German Standard Spec. DIN-1164 or the Japanese Specification JIS-R-5211 which is the same, where the ratio of the percentage contents of the oxides

$$\frac{CaO + MgO + Al_2O_3}{SiO_2} \geq 1$$

should be greater than unity for adequate reactivity.

$$= \frac{7.63 + 1.97 + 5.13}{34.84} = 0.43$$

Therefore, this sample of granulated slag would not be considered hydraulic but pozzolanic.

Secondly, the more basic the slag, the greater its hydraulic activity in the presence of alkaline activators. The hydraulic value increases with the CaO/SiO_2 ratio up to a limiting point when increasing CaO content makes granulation to a glass difficult.

The hydraulic value of other slags, using the German Specification DIN-1164 are:

Inco-Sudbury	- 0.39
Thompson	- 0.35
Falconbridge	- 0.44
Stelco (National Slag)	- 1.87

Stelco	CaO/SiO_2 ratio	-1.17
Texasgulf	"	-0.24

cont.....

The Texasgulf slag, if it is not changed from the Mitsubishi sample, will react as a pozzolan -- -- a pozzolan is a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitous value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

The physical tests, yet to be done, will reveal what value can be placed on this granulated slag product.

Best regards.

Yours very truly,

T.R.Walton.
Technical Sales.

TRW/jv.

c.c. Dr. C.Yu.
Mr. J.McDonnell
Mr. N.A.Anderson
Mr. W.A.Smith
Mr. T.Dowe.

Slag
2nd report

1+3E

ONTARIO REGION

February 27, 1979

Mr. M.D.Street,
Production Superintendent,
Brunswick Mining & Smelting Corp. Ltd.,
Smelting Division,
Belledune, New Brunswick
EOB 1GO

Dear Mike:

Re: Pozzolanic Tests - B.M.&S. Granulated Lead Slag

The pozzolanic activity tests with lime at 7 days was only 42 psi, the minimum required ASTM C-595 is 800 psi.

The compressive strength must be affected by the presence of the small amounts of lead and zinc oxides or corresponding sulphides which very seriously retard the hardening of Portland cement mortars.

In the handbook "The Chemistry of Cement and Concrete by Lea" it states that - the addition of 0.001 percent lead oxide soluble in lime-water has been found to delay the set of Portland cement, but lead salts insoluble in lime-water do not appear to have an adverse effect. Further, it states - with large additions of lead oxide, such as 1 per cent, little sign of setting occurs.

The addition of less than o.1 per cent zinc oxide similarly retards the set and diminishes the strength at early ages.

We would like to test this slag again, when and if, the fuming furnaces are added to the smelter.

Yours very truly,

T.R.Walton,
Manager - Mining Services.

c.c. Mr. F.J.Grebenc, Mine Supt.
Brunswick Mining & Smelting Corp Ltd.,
P.O.Box 3000
Bathurst, New Brunswick
E2A 3Z8

- R. Peacock
Sales Mgr. - Atlantic Region

RESEARCH PROJECT 208123 - Brunswick Mining & Smelting Corp. Ltd., - Lead Slag

DENSITY - 4.45 g/cm^3
- ground to 3180 sq. cm/gm Blaine

POZZOLANIC ACTIVITY WITH LIME, ASTM C-595
- 7 days 42 psi, minimum required 800 psi

POZZOLANIC ACTIVITY WITH MC3 CEMENT, ASTM C-618

Control 28 days	4,803 psi
Test	3,643 psi
Pozzolanic Activity	75.8% required 75%

MORTAR CUBES, ASTM C-109 - would not set -
after 28 days in mounds the cubes fell apart.

GLASS COUNT- the slag sample contains very low glass content; - the actual value was difficult to establish because it was opaque.

CANADA CEMENT LAFARGE LTD.
Research Laboratory
P.O. Box 398, Belleville, Ont.

FEB 14 1979

208123 – Burnswick, Lead Slag

Density 4.45 g/cm³ ; Ground to Blaine 318 m²/kg

Pozzolanic activity with lime, ASTM C595 :–

7 days (42) psi ; 0.290 MPa

Pozzolanic activity with MC3 Cement, ASTM C618 :–

Control 28 days	4803 psi,	(24.6)	MPa	25.1
Test	3643 psi,	(25.1)	MPa	24.6
Pozzolanic activity	75.8 %			

Mortar Cubes, ASTM C109 – would not set – after 28 days in moulds the cubes fell apart.

Glass Count – See attached memo from Dr. H. Chen.

To: T. R. Walton ✓
W. S. Weaver
FEB 12 1979

P. S. Grundstad

MEMORANDUM

To P. S. Grindrod Feb. 12 19 79

From H. Chan Subject 208173

This slag sample contains very low glass content, but the actual value was difficult to establish because it was opaque.

✓

H-C

FEB 12 1979

CANADA CEMENT LAFARGE LTD.
Research Laboratory
P.O. Box 398, Belleville, Ont. K8N 5A3

CANADA CEMENT LAFARGE LTD.
Research Laboratory
P.O. Box 398, Belleville, Ont.

Jan 10/1979

To: Mr. P.S. Grindrod

From: D.G. Stevenson

Re: Project 208123
Brunswick Mining & Smelting Corp. Ltd.
Lead Slag

Wet Chemical Analysis

SiO_2	20.00
Al_2O_3, TiO_2, P_2O_5	9.04
FeO	29.55
Fe_2O_3	6.08
CaO	17.41
MgO	6.86
Na_2O	0.31
K_2O	0.15
Acid Sol SO_3	0.05
S (sulphide)	1.18
Loss @ 1050°C.	(+3.01)
TOTAL	90.63

12

D.S.

FEB 12 1979

FORM GA-200

CANADA CEMENT LAFARGE LTD.

December 14, 1978

Mr. F.J.Grabenc,
Mine Superintendent,
Brunswick Mining & Smelting Corp. Ltd.,
P.O.Box [illegible],3000
Bathurst, New Brunswick.
E2A 3Z8

Dear Mr. Grabenc:

Re: Pozzolanic Tests - B.M.& S. Granulated Lead Slag

A sample of the lead slag is being forwarded to our Belleville, Ontario Research Laboratory by Mr. M. Street of B M & S smelter division. The following tests will be undertaken to determine the pozzolanic qualities of this granulated slag:

1) Grind the slag to 3,000 sq. cm/gm Blaine(approx 85% passing 325 mesh) - normal portland cement is approximately 3,500 Blaine.

2) Glass count

3) Chemical analysis and specific gravity

4) Mortar strength - ASTM-C-109

5) Pozzolanic activity with lime, ASTM -C-595 at 7 days

6) Pozzolanic activity with Normal Portland cement ASTM-C618 at 28 days.

If the granulated slag, has pozzolanic qualities, the next step would be a complete test program. This would allow uniaxial and triaxial testing to be undertaken at the various cement-tailing-slag ratios that would be applicable in Brunswick Mining's underground backfill operations.

We have enclosed copies of the pozzolanic tests we Conducted for four other mining companies, using nickal and copper slags.

The combination of cement, ground slag, and tailings, in various ratios, has in the majority of uniaxial compressive strength tests yielded higher strengths than the equivalent cement-tailing ratios.

2.....

COPY

FORM GA-

CANADA CEMENT LAFARGE LTD.

Copies of the test results will be mailed to you when they are completed.

Yours very truly,

T.R.Walton,
Manager-Mining Services

c.c. R. Peacock
Sales Mgr - Atlantic region

COPY

JEGEL
86018

APPENDIX D

CANMET STUDY ON PROPERTIES AND STRENGTH DEVELOPMENT ON NONFERROUS SLAGS

D1 to D39 Douglas, E. and Malhotra, V.M., "A Review of the Properties and Strength Development of Non-Ferrous Slags and Portland Cement Binders", Report No. 85-7E, Canada Centre for Mineral and Energy Technology, Ottawa, March 1985. [40]

A REVIEW OF THE PROPERTIES AND STRENGTH DEVELOPMENT OF NON-FERROUS SLAGS AND PORTLAND CEMENT BINDERS

E. Douglas and V.M. Malhotra

Mineral Processing Laboratory

MINERAL SCIENCES LABORATORIES
CANMET REPORT 85-7E

March 1985

© Minister of Supply and Services Canada 1986

Available in Canada through

Authorized Bookstore Agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

Catalogue No. M 38-13/85-7E
ISBN 0-660-12032-1

Canada: $4.25
Other countries: $5.10

Price subject to change without notice

A REVIEW OF THE PROPERTIES AND STRENGTH DEVELOPMENT OF NON-FERROUS SLAGS AND PORTLAND CEMENT BINDERS

E. Douglas and V.M. Malhotra***

SYNOPSIS

This study presents a state-of-the-art review of the advances in research and in practical applications of copper, nickel, and lead slags as partial portland-cement replacement in cemented mine backfill and in concrete. Recent research shows that glass content and pozzolanic properties of non-ferrous slags are not directly related and that grindability of the slags seems to be a function of the degree of vitrification. Compressive strength tests on mortars show that air-cooled, non-ferrous slags can outperform granulated slags, depending on the fineness. During hydration, the slags seem to accelerate the rate of C_3S hydration but do not seem to react immediately with the $Ca(OH)_2$ liberated. Non-ferrous slags appear to have considerable potential for partial portland-cement replacement in cemented mine backfill and, to a degree, in concrete. Research is needed to define the areas of additional applications, as well as limitations, to the use of non-ferrous slags.

*Research Scientist, Construction Materials Section, CANMET, Energy Mines and Resources Canada, K1A 0G1.

**Head, Construction Materials Section, CANMET, Energy Mines and Resources Canada, K1A 0G1.

EXAMEN DES PROPRIÉTÉS ET DE LA RÉSISTANCE DES LIANTS COMPOSÉS DE LAITIER NON FERREUX ET DE CIMENT PORTLAND

E. Douglas et V.M. Malhotra***

RÉSUMÉ

Le présent document contient une analyse récente des progrès réalisés au niveau de la recherche et des applications pratiques du laitier de cuivre, de nickel et de plomb comme matériau de remplacement partiel du ciment Portland dans le remblai aggloméré des mines et dans le béton. Les résultats de recherches récentes indiquent que la teneur en verre et les propriétés pouzzolaniques du laitier non ferreux ne sont pas directement reliées et que la friabilité du laitier semble varier selon le degré de vitrification. Des essais de résistance à la compression effectués sur des mortiers démontrent que le laitier non ferreux refroidi à l'air peut donner un meilleur rendement que le laitier granulé et ce, suivant sa finesse granulométrique. Pendant l'hydratation, le laitier semble accélérer le taux d'hydratation du C_3S, mais ne semble pas réagir immédiatement avec le $Ca(OH)_2$ libéré. Le laitier non ferreux semble offrir de grandes possibilités en tant que substitut partiel du ciment Portland dans le remblai aggloméré des mines et, jusqu'à un certain point dans le béton. Il est nécessaire de poursuivre les recherches afin de déterminer les secteurs qui se prêtent à de nouvelles applications de même que les limites qui restreignent l'utilisation du laitier non ferreux.

*Chercheur scientifique, Section des matériaux de construction, CANMET, Énergie, Mines et Ressources Canada, K1A 0G1.

**Chef, Section des matériaux de construction, CANMET, Énergie, Mines et Ressources Canada, K1A 0G1.

CONTENTS

SYNOPSIS iii
RÉSUMÉ v
INTRODUCTION 1
NATURE OF NON-FERROUS SLAGS 2
Chemical Composition 2
Glass Content 2
PROPERTIES OF NON-FERROUS SLAGS 2
Grindability 2
Pozzolanic Activity 3
Effect of glass content on pozzolanic activity 3
Effect of fineness on pozzolanic activity 4
HYDRATION OF NON-FERROUS SLAGS 4
STRENGTH DEVELOPMENT OF MINE BACKFILL MATERIAL INCORPORATING NON-FERROUS SLAGS 5
STRENGTH DEVELOPMENT OF MORTARS AND CONCRETE INCORPORATING NON-FERROUS SLAGS 6
Effect of Glass Content on Strength Development 6
Effect of Fineness on Strength Development 7
Effect of Slag Content on Strength Development 7
Effect of Activators on Strength Development 7
DURABILITY OF MORTARS INCORPORATING NON-FERROUS SLAGS 8
CONCLUDING REMARKS 8
Suggested Research 8
REFERENCES 9

TABLES

1. Chemical analysis of Canadian non-ferrous slags 13
2. Bulk composition of Canadian non-ferrous slags 13
3. Copper slag constituents determined by image analysis 13
4. Compositions of glass determined by electron microprobe in copper slags 13
5. Estimated kWh/t required to grind nickel slag, calculated from grinding times 13
6. Particle-size distribution of granulated nickel slag ground to 3000 cm^2/g 14
7. Size distribution, surface area, and specific gravity of ground slags tested for pozzolanic activity 14
8. Energy consumption for grinding non-ferrous slags 14
9. Grinding energy requirements and compositional characteristics of non-ferrous slags 15
10. Slag activity index of non-ferrous slags cured in moist room at 23°C for 50% portland-cement replacement by absolute volume 15
11. Chemical composition of air-cooled and of quenched nickel slags 16
12. Composition of the specimens incorporating air-cooled and quenched nickel slags 16
13. Pozzolanic and slag activity indexes of portland cement-slag mortars cured at room temperature 16
14. Pozzolanic and hydraulic indexes of Canadian non-ferrous slags 17
15. Relative strength of portland cement-nickel slag mortars showing the effect of fineness 17
16. Uniaxial compressive strength of ground copper reverberatory furnace slag and $Ca(OH)_2$ pastes 17
17. Effect of density and water content on compressive strength of fill at an early age 17
18. Mix proportions for cemented-mine tailings and compressive strength development 18
19. Cemented rockfill mix proportions and compressive strength development of rockfill 18
20. Compressive strength at 28 days of mortar cubes cured at 38°C with 20, 35, 50, and 70% absolute replacement of portland cement by slag 19
21. Compressive strength at 23°C of mortar cubes with 50% absolute volume replacement of portland cement by slag 20
22. Gradations of coarse and fine aggregates for concrete mixes 20
23. Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement of CSA Type 10 portland cement 21
24. Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement of Type 10 portland cement, with water-reducing admixtures 22

FIGURES

1. Production, location, and utilization of non-ferrous slags from Canadian sources 25
2a. Representation of some cementitious materials in the system $CaO-SiO_2-Al_2O_3$ 26
2b. Representation of some cementitious materials in the system $CaO-SiO_2-Fe_2O_3$ 26
3. Energy consumption for production grinding of non-ferrous slags 26
4. Curing curves demonstrating strengthening effect of ground copper reverberatory furnace slag acting as a pozzolan with different cement contents 27
5. Curing curves at 1, 2, 3, and 4 wt % portland cement and various copper reverberatory furnace slag additions, as indicated on individual curves 28
6. Effect of ground granulated slag on uniaxial compressive strength of consolidated fill containing 6% portland cement 29
7. Compressive strength development at 23°C in moist-cured mortars containing 50% slag by absolute volume replacing portland cement 29
8. Compressive strength of copper slags-portland cement mortars at 28 days curing 30
9. Compressive strength of nickel slags-portland cement mortars at 28 days curing 30
10. Compressive strength of lead slags-portland cement mortars at 28 days curing 31
11. Change in strength at different curing ages calculated on basis of standard 4.8 wt % portland-cement specimens cured to same age during pozzolanic testing at various cement replacement levels 31
12. Hydraulic index of air-cooled and of granulated nickel slags of different fineness 32
13. Compressive strength of Type III portland cement-lead slag binders at various cement replacement levels 32
14. Strength development in portland cement-copper slag mortars cured at room temperature 33
15. Compressive strengths of concrete mixes 34
16. Compressive strength ratios of concrete mixes 34
17. Strength development in portland cement-copper slag mortars cured at room temperature 35
18. Effect of fineness on compressive strength of 70 wt % portland cement and 30 wt % air-cooled nickel slag binders 36
19. Effect of slag content of binders on compressive strength of mortar cubes 36
20. Relation between combined water and compressive strength 36
21. Effect of activators on compressive strength of air-cooled and granulated nickel slags ground to various finenesses 37

INTRODUCTION

Wastes generated by the mining, mineral, and metallurgical processes contain metallic and mineral materials that are recoverable. Growing interest in such wastes has been caused by increasing exploration, mineral beneficiation, increasing cost of waste disposal, exhaustion of favourably located high-grade mineral deposits, and legislation restricting mining operations near populated areas. These facts have prompted studies on the feasibility of recovering metals and minerals from more accessible mineral ore and from sources such as mineral wastes.

Basically, most of those mineral wastes not dumped in waste dumps are used as fillers, soil additives, aggregates, and railroad ballast. More important, however, are both the utilization of mineral wastes (such as slags) as portland-cement replacement in cemented mine backfill and in concrete, and the realization that mineral wastes are byproducts in which significant energy had been invested and lost through disposal (Fig. 1). Vitrification and grinding of ferrous wastes, such as blast-furnace slag, produces a material that can be added at the mixer as portland-cement replacement in concrete manufacturing (1).

In Canada, vitreous (pelletized) iron blast-furnace slag is produced at a rate of 2.2×10^5 metric tons per annum in Hamilton, Ontario. In Sault Ste. Marie, Ontario, a plant is under construction to produce 200 000 metric tons per annum of granulated blast furnace slag at the Algoma steel plant. Approximately 45% of the blast-furnace slag produced in Hamilton is used in concrete manufacture (2).

Although the technology of utilization of granulated ferrous slags as cementing materials has been developed in Europe and North America, the utilization of non-ferrous slags as cementitious materials is not well established in concrete manufacture (3,4). The use of copper slags in mine backfill is current practice in Australia, where about 50% of the portland cement used in mine backfill at Mount Isa, Queensland, has been replaced by granulated ground copper slag, resulting in lower production costs (3).

In Europe, Australia, and Canada some copper, nickel, and lead slags have been evaluated for performance as cementitious components in mine backfill (4,5,6) and in concrete (7,8). Approximately 4.1×10^6 metric tons per annum of non-ferrous slags are produced in Canada, of which little is used as railroad ballast and engineering fill. The current accumulation amounts to about 17×10^6 metric tons.

Ferrous slags are siliceous or alumino-siliceous byproducts of metallurgical processes. These slags possess little or no cementitious value, but in finely divided form and in the presence of moisture they react with alkali and alkaline earth hydroxides* at ordinary temperatures to form compounds possessing cementitious properties (9). Under the same conditions, cementitious properties can be conferred on non-ferrous slags.

Copper and nickel slags are extracted from sulphide concentrates by pyrometallurgical treatment. The process includes three different operations:

- ***roasting***, in which sulphur is eliminated as SO_2 and iron is oxidized;
- ***smelting***, in which the product of roasting is melted with a siliceous flux, forming a liquid iron silicate slag which floats on the heavier molten sulphide matte;
- ***converting***, in which sulphur is driven off the sulphide melt and the remaining iron is oxidized and fluxed for removal as a silicate slag.

Converter slag is usually returned to the smelter since it is rich in metal content, whereas smelter slag is either discarded without further treatment or granulated with excess water. These slags possess a high degree of hardness and porosity and vary in unit weight and chemical composition because of differences in ore type, furnace or smelter operations, and slag cooling procedures.

This study is a state-of-the-art review of the advances in research and in practical applications of copper, nickel, and lead slags. It is expected that a critical review could direct future research toward the use of significant amounts of a valuable resource.

*This refers to NaOH, KOH, and $Ca(OH)_2$.

NATURE OF NON-FERROUS SLAGS

CHEMICAL COMPOSITION

Despite the differences in process types, the slags are of similar chemical composition and all may be considered to be represented in the CaO-SiO_2-Fe_2O_3 system (Fig. 2).

The bulk composition of some Canadian slags is shown in Table 1 (10). A recent study on the characterization of Canadian non-ferrous slags (Table 2) shows that determination of the bulk chemical composition with an electron microprobe, operated at 15 kV accelerating voltage, differs somewhat from the chemical composition determined by analytical methods (11).

GLASS CONTENT

Data have been published by McGuire (12) on the glass content of non-ferrous slags from Canadian sources such as a nickel-copper electric furnace slag granulated by quick quenching. The glass content was measured by X-ray diffraction and reported to be 95% (13). The slag was too opaque for a reliable glass count by the optical method using polarizing light, similar to that adopted for quality control of iron blast-furnace slag (14).

Measurements of glass content by a method that uses scanning electron microscopy (SEM) and image analysis were reported by Douglas et al. (15) in a study on the hydration and the pozzolanic activity of ambient-cooled, and of quenched, copper reverberatory furnace* slags from Northern Quebec (Table 3). The glass content in the *air-cooled* slag was 45%; in the *quenched* slag, it was 75 to 95%. The composition of the glass was also reported (Table 4), showing the difference between the glass in the air-cooled slag and the quenched slag due to segregation of Al_2O_3, SiO_2, K_2O, and CaO during quenching. The results did not agree with those published by Roper et al. (16) who estimated a ratio of amorphous-to-crystalline phase of approximately 1:1 in a quenched copper reverberatory slag.

PROPERTIES OF NON-FERROUS SLAGS

GRINDABILITY

Information on grindability, energy requirements for grinding, and particle size distribution of ground non-ferrous slags is limited. Laneuville (5) reported the estimated power required to grind air-cooled and granulated nickel slags to various finenesses based on the duration of the grinds (Table 5).

The particle size distribution of a nickel-copper electric furnace slag, ground to a specific surface of 3 000 cm^2/g, was reported by McGuire (12) and is shown in Table 6. Size distribution of ground nickel slags from Copper Cliff, Ontario, tested for pozzolanic activity is shown in Table 7 (17).

More recently, a study by Douglas et al. (10) on the grindability of a number of Canadian copper, nickel and lead slags compared it with that of a portland-cement clinker containing 3% gypsum. For calibration of grinding time and energy consumption, the grinding energy requirement for portland-cement clinker with 3% gypsum was taken as 31 kWh/t to develop a specific surface of 3 000 cm^2/g and 43 kWh/t to develop a specific surface of 4 000 cm^2/g. From this information about grinding energy consumption, a scale-up from laboratory mill to typical production mill was estimated as 1 min = 0.4 kWh/t, which is a value dependent on the specific laboratory.

Grinding data are given in Table 8, in terms of initial gradation, actual fineness (Blaine method), time to achieve specific fineness, and energy consumption for producing materials of 2 000, 3 000, 4 000 and 5 000 cm^2/g as well as specific gravity and per cent passing 45 μm (10).

Figure 3 shows the estimated energy consumption required for production grinding of the slag samples compared to that required to grind blast-furnace slag and portland-cement clinker with addition of gypsum to a specific surface of 4 000 cm^2/g. Grinding energy in increasing order, a comparison to an initial minus 75 μm size, major oxide composition, and estimated degree of vitrification are given in Table 9 (10).

From the data collected, it would appear that the grindability of non-ferrous slags is a function of the degree of vitrification. Slags with higher glass contents generally require more grinding time.

*A reverberatory furnace is a furnace in which smelting of the concentrate takes place.

POZZOLANIC ACTIVITY

Pozzolanic materials contain fine, active silica which reacts with lime and water to form stable cementitious, hydrated calcium silicates. For hydraulic cement mine backfill, fly ash, ground quenched copper reverberatory furnace slag, and ground blast-furnace slag are materials with proven pozzolanic activity (16). According to Thomas (18), three aspects have to be considered in the use of pozzolanic materials for hydraulic cemented mine backfill:

- — reaction causing removal of lime, a material with potentially adverse effects;
- — production of a stronger cement due to removal of lime, allowing strength development at a lower portland cement content;
- — formation of additional cementing materials from the pozzolanic reaction, resulting in equivalent strength at lower portland cement content.

Experimental evidence of this approach was found by Thomas (3) in the results of a study on the pozzolanic properties of a granulated copper reverberatory furnace slag which showed no obvious alteration after many years in a surface dump. The particle size analysis revealed essentially one component, approximately 2.54 mm in diameter. Test specimens were prepared from pulped mixtures of fill, portland cement, and the slag ground to a specific surface of 3 000 cm^2/g. Strength increases with increasing slag additions at fixed cement content are shown in Figure 4. These results, concerning cost reductions in cemented fill production with no strength loss, were considered significant.

The same slag was tested at a later date in cemented mine fill at high slag/cement ratio (6). The fill contained 80 to 99 wt % of Isa Mine copper sulphide tailings, 1 to 5 wt % portland cement and 0 to 16 wt % slag (Fig. 5). Thomas (6) concluded that slag additions, indicated as non-beneficial at 1 wt % portland cement, were consistently beneficial at 3 and more wt % portland cement, and transitional in benefit at 2 wt % portland cement.

Pozzolanic activity tests on a granulated copper slag were carried out by various methods in Spain (4). The results of tests performed in accordance with ASTM C 618-73 method showed strength above 75 wt % of the control specimens.

Laneuville (5) determined the pozzolanic activity of air-cooled and of granulated nickel slags by ASTM C 595 method and reported that compressive strengths higher than the minimum 800 psi set out in the specifications were obtained with these slags ground to a specific surface in the range 3 800 to 4 000 cm^2/g.

In Canada, strength gains with increasing contents of a granulated nickel-copper electric furnace slag were measured by McGuire (12) in mixes containing 6 wt % of portland cement and a tailing fill of 2.96 relative density (Fig. 6). The strength gains were attributed to chemical bonding, derived from the hydration of a pozzolanic slag.

More recently, slag activity and pozzolanic indexes were determined in accordance with ASTM C 109* for the preparation of the test specimens, and with ASTM C 595** and C 989*** (10) for curing and testing.

Tests were conducted at age 7 and 28 days according to a modified ASTM C 989 standard, where 50% of portland cement measured by absolute volume, was replaced by the ground non-ferrous slag, thus taking into account the different specific gravity of the slags (Table 10).

Significant strength development due to pozzolanic activity is shown in Figure 7. The strength development for 28 days curing at 38°C, for mortars with 20, 35, 50 and 70% ground non-ferrous slag replacing portland cement, is shown in Figures 8 to 10. Activators, such as NaOH, and the replacement of portland cement by cement kiln dust did not improve compressive strengths (10).

Effect of glass content on pozzolanic activity

The effect of glass content on the pozzolanic properties of Canadian non-ferrous slags can be assessed by comparing strength development data of air-cooled and of water-quenched slags (5,19).

---

*ASTM C 109: Compressive strength of hydraulic cement mortars using 50 mm cube specimens.

**ASTM C 595: determination of pozzolanic activity and of slag activity index with portland cement on specimens cured in a moist room at 23°C for 24 h, and at 38°C in sealed containers after removing from the mold, for the balance of the time, to 28 days.

***ASTM C 989: determination of slag activity with portland cement. The following specifications were introduced: (a) replacement of 50% of the portland cement by the slag was done by absolute volume and not by weight, and (b) the specimens were cured at 23°C in the moist room to the specified age.

Pozzolanic activity tests of binders for mine backfill were performed in Canada (20) with air-cooled and with quenched nickel and copper-nickel slags at different cement replacement levels. The chemical composition of the slags tested and the mixture proportions of the cemented backfill from which the test specimens were cast are listed in Tables 11 and 12.

Glass content of the air-cooled nickel reverberatory slag was estimated at less than 20%. The change in compressive strength was calculated on the basis of a standard incorporating 4.8 wt % of portland cement (Fig. 11). Maximum changes in strengths were observed after 14 days of curing for a sample incorporating 60% of air-cooled nickel slag. For unknown reasons, better performance occurred in long-term curing of test specimens of a mix incorporating an air-cooled, rather than water-quenched, copper-nickel slag. The mix contained 4.8% cement, 1.2% slag, and 96% tailings.

Results from recent studies on pozzolanic activity of Canadian air-cooled and of quenched non-ferrous slags (10,15) led to the conclusion that, (contrary to results of studies on blast-furnace slag), for non-ferrous slags the glass content and pozzolanic activity are not directly related. Test specimens of mortars with 35 and 70% cement replacement were prepared according to ASTM C 595, but cured at room temperature (15). Results of pozzolanic activity studies (Table 13) indicate that air-cooled copper slags could, depending on their fineness, outperform–or at least equal–the performance of quenched copper slags. Similar results were reported on pozzolanic tests carried out on granulated nickel, copper, and lead slags, according to ASTM C 595 (21). Pozzolanic and slag activity indexes are shown in Table 14.

Effect of fineness on pozzolanic activity

Laneuville (5) evaluated the relative strength of mortars prepared in accordance with ASTM C 109, in which 30% of the cement was replaced by air-cooled nickel slag, ground to different finenesses. The strength of the test specimens was compared to that of a portland-cement mortar at various curing ages (Table 15). *The experimental results indicate that compressive strengths are directly related to fineness*. Laneuville (5) also studied the effect of fineness on the hydraulic index at different curing ages (Fig. 12).

The data indicate that granulated slags ground to 3 000 cm^2/g performed better than air-cooled slags ground to 4 000 cm^2/g. Nevertheless, air-cooled slags ground to 7 000 cm^2/g performed better than the rest of the slags (Table 15). A more recent study indicates that the effect of fineness on the pozzolanic activity of Canadian copper, nickel, and lead slags, for both air-cooled and quenched samples, is directly related to pozzolanic activity as shown in Tables 13 and 14 (21).

HYDRATION OF NON-FERROUS SLAGS

Chemically, inorganic cementing materials derive from the multi-component system:

$$CaO\text{-}MgO\text{-}SiO_2\text{-}Al_2O_3\text{-}Fe_2O_3\text{-}SO_3$$

Portland cement, natural pozzolans, most fly ashes and many blast-furnace slags may generally be considered on a simplified ternary system $CaO\text{-}SiO_2\text{-}Al_2O_3$ with minor or insignificant amounts of MgO, SO_3 and Fe_2O_3 (Fig. 2a). Steel slags and non-ferrous slags are better represented by the system, $CaO\text{-}SiO_2\text{-}Fe_2O_3$, where CaO represents the sum of CaO, MgO and Al_2O_3 (Fig. 2b).

Approximately 70 to 75 wt % of portland-cement clinker is tricalcium silicate (C_3S) and β-dicalcium silicate ($\beta\text{-}C_2S$) with small amounts of Al_2O_3 and MgO dissolved in them (22). In addition, small amounts of calcium sulphate, usually in the form of gypsum, are added to portland-cement clinker during the grinding operation for the purpose of controlling the initial hydration reactions.

Natural pozzolans of volcanic origin are composed of a vitreous phase of microporous texture with small amounts of a crystalline phase (23). The silica and alumina, that constitute the vitreous pyroclastic component, combined with lime in aqueous media yield insoluble cementitious products. The reactivity of pozzolans is determined not only by the structure, morphology, and chemical composition of the vitreous phase, but also by the fineness of the material (24), type and quantity of lime in the system (25,26) and water content (27).

Different hydration products have been identified on various pozzolan-$Ca(OH)_2$ systems. In some cases, C-S-H together with C_2ASH_8, or C-S-H,C_2ASH_8, hydrogarnet and ($C_3A.CaCO_3H_{12}$-C_4AH_{13}) were found, depending on the composition of the pozzolan. The CaO/SiO_2 ratio in the C-S-H is believed to be closely related to the concentration of Ca^{2+} in the solution (28).

The composition of slags depends on their origin. Copper slags analyzed by scanning electron microscopy (SEM) (15) show that slags appear as intergrowths of fayalite, spinel, glass and copper sulphides. Results of optical and SEM studies carried out in Spain (4) on granulated copper slags showed that the crystalline phase was composed mainly by needle-like fayalite (Fe_2SiO_4) and globular iron oxides.

Not much is known about the composition of other slags. It might be expected that materials as diverse as portland cement, pozzolans, and ferrous and non-ferrous slags would react with water to form markedly different compounds. In practice, there is a remarkable similarity in the reaction products from these materials. The common factor in all of these systems is the ultimate formation of C-S-H and the correspondence between its formation and the development of structural bonds in the hydrating mass.

Kam (29) studied the hydration of copper reverberatory furnace slag in the presence of $Ca(OH)_2$, $CaCO_3$, and portland cement. The experimental analysis of the hydration products comprised measurements of early heat of hydration, determination of non-evaporable water in the reaction products, quantitative X-ray diffraction analysis, and scanning electron microscopy.

Kam reported that the rate of heat evolution decreased as the proportion of slag increased. Also, the amount of non-evaporable water increased as the amount of slag in the paste increased. Kam's studies also showed an unidentified diffraction peak at 7.34 Å in the X-ray diffractograms for all the hydrated slag-$Ca(OH)_2$ pastes. The X-ray diffraction study showed also that the fayalite crystals do not take part in the hydration reactions. Such reactions are limited to the glass phase.

Roper et al. (16) reported that copper reverberatory furnace slag need not be completely glassy for significant hydration to occur. Recent investigation by Douglas et al. (15) on an air-cooled copper slag with 41% glass and on a quenched copper slag with 95% glass, showed that the presence of the slag delays the transfer of Ca^{2+} from the portland-cement constituents to the solution at the early stage of hydration.

In the later stage, between 24 and 72 hours of hydration, the measured Ca^{2+} concentration in the solutions in contact with the binders and the percentage of $Ca(OH)_2$ in the solid phase at the same age suggest that more C_3S from the portland cement had reacted in the slag blend than in the portland-cement paste. Although the study showed that air-cooled slags may outperform quenched slags, depending on the fineness, further research in this area is needed.

STRENGTH DEVELOPMENT OF MINE BACKFILL MATERIAL INCORPORATING NON-FERROUS SLAGS

Most of the studies intended to encourage the use of copper, nickel, and lead slags have been directed toward exploring the feasibility of their use as cement replacement in cemented mine backfill. Strength development of copper reverberatory furnace slag, de-zinced lead smelter slag, and copper converter slag in cemented fill were first studied by Thomas (3,6) in Australia and his data are shown in Figures 4 and 5.

Kam in a recent study (29) showed that significant strength could be developed with slag-$Ca(OH)_2$ mixes, where higher $Ca(OH)_2$ content would lead to higher strength (Table 16). Strength development, equivalent to that obtained with portland cement-slag mixes, can be achieved with cemented fill using copper reverberatory furnace slag and lime mixtures (29). Variations in the strength of fill at early ages are mostly affected by density and water content (Table 17), both of which are related to consolidation conditions.

At later ages, variations in strength are affected by the amounts of hydrated cementitious materials in the mix. Improvement in compaction methods of backfill in stopes should be an important goal, if early strength development is required. According to Kam (29), increased compaction could be achieved by rapid drainage of the wet fill as it is being placed, and vibration methods should also be explored. Changes in the grain size distribution of the fill materials, such as rejected slimes, may improve the particle size distribution and therefore the compaction of the fill material.

A recent study by Emery (21) reports tests at 7, 28, and 90 days on a granulated copper slag from Ontario and a remelted and quenched copper slag from Quebec in mixes with mine tailings (Tables 18 and 19). Measurements were made on 50-mm uncompacted cubes containing 70% mine tailing. The cubes were demolded when sufficient strength was obtained; they were stored in the moist room at 23°C; after 28 days the specimens were tested for compressive strength. It was found that little improvement in strength developed in the cementitious systems with 12 wt % slag and 4% portland cement, compared with the blend of 4 wt % slag and 4% portland cement.

A decrease in compressive strength between 28 and 90 days was also reported. It would appear that most of the cementitious properties were due to the portland cement and that lower compressive strength at 90 days may be related to the components in the tailings causing chemical reactions during curing. It is doubtful that this will be a factor in actual applications.

STRENGTH DEVELOPMENT OF MORTARS AND CONCRETE INCORPORATING NON-FERROUS SLAGS

Tests for strength development of mortars incorporating non-ferrous slag binders have been conducted by Laneuville (5) and by Baragano (4) using nickel and copper slags. Reports of research on the use of lead slags as partial portland-cement replacement in steam-cured blocks have been published recently (7). The specimens were made with ground lead slags and calcium-bearing materials such as lime, gypsum, and portland cement. Mixtures had been prepared consisting of 3 parts of sand and 1 part of a binder formed by different combinations of ASTM Type III portland cement and a lead slag ground to 2 500 cm^2/g. The results showed that up to 25 wt % ground slag can replace cement before significant strength loss occurs (Fig. 13).

Tests on strength development of mortars, some incorporating air-cooled, granulated and quenched lead, nickel and copper slags from Canadian sources, have been reported and data are shown in Table 18 (21). Portland cement in the mortar was replaced by the slag. The mortars were cured at 38°C for 28 days. Higher strengths were observed in air-cooled than in quenched nickel slags. Strengths of granulated copper slag from the province of Ontario were slightly improved by adding 20% CaO to the melted slag and quenching in excess water.

Investigations by Emery (21) show that air-cooled copper reverberatory furnace slag from the province of Quebec exhibited higher strengths than the quenched slag from the same source at the same fineness in some of the specimens; some of his data are shown in Table 20. Another series of tests was performed with mortars in which 50% of the portland cement had been replaced by the slag (21). The mortars were cured at room temperature (23°C) and tested at 1, 7, 28 and 90 days (Table 21). The results show that several slags appear to have portland-cement replacement potential at the 4 000 Blaine level.

Douglas and Mainwaring (15) have reported strength development of mortars of portland cement-copper slags binders with 35 and 70% cement replacement. The mortars had been placed in close-fitting containers stored at 23 ± 1.7°C and tested at 1, 7, 28, and 90 days (Fig. 14a,b).

The compressive strength of mortar incorporating 35% of air-cooled slag ground to 4 000 cm^2/g (Blaine method) was higher than that of a mortar incorporating 35% of the quenched slag with the same fineness. At 90 days the strength of the former attained that of the portland-cement mortar used as a control. In mortars with 70% replacement, the mortar incorporating the quenched slags developed higher strength than that incorporating the air-cooled slag.

Other recent studies on Canadian non-ferrous slags showed that some slags ground to 4 000 cm^2/g outperform the corresponding 3 000 cm^2/g materials. However, many of the 3 000 cm^2/g materials are sufficiently reactive to save the extra grinding costs (11).

Details of a recent study on concrete mixes, incorporating Canadian ground non-ferrous slags have been reported (21), and their compressive strength development are shown in Tables 22, 23, and 24. Table 24 shows the effect of a water-reducing admixture on compressive strength development at different ages. Tables 23 and 24 allow comparison of the concrete mixes incorporating ground non-ferrous slags in terms of both compressive strength development at 7, 28, and 90 days, and compressive strength ratio to the control at the same ages.

Figure 15 shows compressive strength development, and Figure 16 the compressive strength ratio. Evidently the compressive strengths of concrete mixes incorporating lead slag at 90 days is equivalent to the compressive strength of the control at 28 days.

EFFECT OF GLASS CONTENT ON STRENGTH DEVELOPMENT

Limited information is available on the relationship between glass content and strength development with time for portland-cement concrete incorporating non-ferrous slag. Results on strength development of non-ferrous slag binders, both air-cooled and quenched, were reported in a Canadian patent (5). Mortars made with 70:30 cement-to-slag ratio were tested for compressive strength (ASTM C 109). Nickel slags were used; air-cooled slags were ground to a specific surface of 4 000 cm^2/g, the granulated slags to 3 800 cm^2/g. Results to 90 days of curing indicated that water quenching improved the long-term strength of glassy nickel slag binders.

Douglas et al. (30) have reported tests on strength development of mortars (ASTM C 109) incorporating air-cooled, granulated and quenched lead, nickel and copper slags from Canadian sources. With each test, a different amount of portland cement in the mortars was replaced by the slags. The mortars were cured at 38°C for 28 days. Higher strengths were observed in air-cooled than in quenched copper slags (Fig. 14). Strengths of granulated copper slag from the province of Ontario were slightly improved by adding 20% CaO to the melted slag and quenching in excess water. Air-cooled copper reverberatory furnace slag from the province of Quebec exhibited higher strengths than the more glassy quenched slag from the same source in some of the specimens.

Another series of tests was performed with mortars (ASTM C 109) in which 50% of the portland cement was replaced by the slag (31). The mortars were cured at room temperature (23°C) and tested at 1, 7, 28, and 90 days (Table 21). The results show that some slags ground to 4 000 cm^2/g and cured at 90 days outperformed the control specimens.

Strength development in mortars of portland cement-copper slag binders with 35 and with 70% cement replacement was recently reported by Douglas and Mainwaring (15). The mortar cubes (ASTM C 595) were tested at 1, 7, 28, and 90 days (Fig. 17). The compressive strength of mortar incorporating 35% of air-cooled slag ground to 4 000 cm^2/g (Blaine method) was higher than that of a mortar incorporating 35% of the more glassy quenched slag. At 90 days the strength of the former attained that of the portland-cement mortar used as control.

EFFECT OF FINENESS ON STRENGTH DEVELOPMENT

Improved strengths of finer granulated blast-furnace slags reported in the literature (32) led some investigators to study the effect of fineness in strength development of nickel slag binders (5). Compressive strength data were reported on mortars (ASTM C 109) containing 70% portland cement and 30% air-cooled nickel slag. The mortars were cured in water at 23°C. An increase of approximately 15% in compressive strength after 90 days was observed for specimens made with slags ground to 4 000 cm^2/g, compared to those slags ground to 3 000 cm^2/g.

Data on mortars made with an air-cooled nickel slag of similar chemical composition but with a MgO content 2% higher than in the first sample were also reported (5). Strength development of the two air-cooled slags was approximately the same when ground to a specific surface of 4 000 cm^2/g. Increasing the specific surface to 7 700 cm^2/g resulted in approximately 15% increase of compressive strength at 90 days. Strength development of mortars incorporating air-cooled nickel slag ground at different fineness and cured at 23°C are shown in Figure 18 (5). Compressive strengths at 28 days of mortars incorporating lead, nickel or copper slags ground to 2 000, 3 000, 4 000 and 5 000 cm^2/g were reported in Canada (Table 21) (29).

EFFECT OF SLAG CONTENT ON STRENGTH DEVELOPMENT

Apparent discrepancies have been reported on the effect of slag content on the strength development of nickel slag binders. Thomas (33) found increasing strength in mixes of tailings with a fixed amount of portland cement and copper slag content about double that of cement.

Laneuville (34) reported negligible contribution of a granulated nickel slag to early age strength and a progressively greater contribution after 90 days of wet curing at 21°C for binders containing less than 45% slag (Fig. 19).

The discrepancy between the two sets of results, those of Thomas and those of Laneuville, was explained by Laneuville in terms of the decreasing ratio of water to cementitious materials when larger amounts of slag are added to a constant amount of portland cement. Measurements of the combined water in mortars of slag binders showed a direct relationship between compressive strength and combined water (Fig. 20).

EFFECT OF ACTIVATORS ON STRENGTH DEVELOPMENT

Low compressive strength values at early ages obtained in mortars with 65:35 portland cement to copper slag ratio led researchers to the study of the effect of alkaline activators on early strength (4). Atwell (1) reported that when 5 to 10% of precipitator dust with an alkali oxide content of approximately 5% was added to mortars made with portland cement-copper slag blends, an increase of up to 25% in compressive strength at 7 days was observed.

The effect of calcium carbonate and calcium chloride on air-cooled and on granulated nickel slag was investigated by Laneuville (5) in mortars with 30% portland-cement replacement with slag. He concluded that the compressive strength of nickel slag mortars does not improve by increasing its basicity.

Activation with calcium chloride was found effective for improving the performance of air-cooled slags after 7 days curing (Fig. 21). The results showed improvement of strength at all ages in granulated slags with addition of 2% calcium chloride.

Laneuville (5) tested the effectiveness of precipitator dust used as an activator. The kiln dust contained 16.8% potassium oxide and 9.5% free calcium oxide. He concluded that the incorporation of cement precipitator kiln dust in portland cement-nickel slag binders yielded binders with improved early strength characteristics and properties close to those of portland-cement mortars.

Recent studies, however, indicate that the activation of lead, nickel, and copper slags by addition of Na(OH) to the mixing water, at a concentration of 200 g/L, or by replacing portland cement by cement kiln dust, does not result in satisfactory performance (10).

DURABILITY OF MORTARS INCORPORATING NON-FERROUS SLAGS

The performance of concrete with partial replacement of cement by non-ferrous slags possessing pozzolanic properties is not known. Baragano (4) reported results of tests on mortars on the protective capacity against corrosion for steel reinforcement. Good results were observed for copper slag-cement blends without addition of calcium chloride as an activator.

Baragano (4) has also reported results on tests for resistance to sulphate attack on mortars with copper slag-portland cement blends. Calcium, magnesium and sodium sulphate solutions as well as sea water were used as aggressive agents. The greatest resistance was shown by a slag cement with 35% copper slag, compared with portland-cement mortar or with portland cement blended with 35% natural pozzolan. Similarly, the freezing and thawing tests on mortars indicated better performance with copper slag than with natural pozzolan.

CONCLUDING REMARKS

1. Non-ferrous slags appear to have considerable potential for partial portland-cement replacement in cemented mine backfill and in concrete.

2. Additional research work needs to be done to define areas of applications as well as limitations on the use of non-ferrous slags.

SUGGESTED RESEARCH

A research program directed towards the use of non-ferrous slags in cemented mine backfill and concrete should include:

1. development of standards for quality control;
2. development of tests for detection of potential health hazard due to leaching of deleterious elements;
3. tests for resistance of concrete to external agents.

REFERENCES

1. Atwell, J.S. "Some properties of ground granulated slag"; *Proc Inst Civ Eng* 57:12; 1974.

2. Douglas, E. "Canadian ferrous and non-ferrous slags for resource and energy conservation"; *Division Report* ERP/MSL 83-61(TR); CANMET, Energy, Mines and Resources Canada; 1983.

3. Thomas, E.G. "Cemented fill practice and research at Mount Isa"; *Proc Aust Inst Min Met* 240; 1971.

4. Baragano, J.R. and Rey, P. "Estudio de una puzzolana no tradicional: escoria de cobre"; *Asland*; Division de Tecnologia y Servicio; Informe No. 977; 1980.

5. Laneuville, J. "Portland cement-slag binders"; *Canadian Patent No.* 963482; Patent Office; Ottawa; 1975.

6. Thomas, E.G. and Cowling, R. "Pozzolanic behaviour of ground Isa Mine slag in cemented hydraulic mine fill at high slag/cement ratios"; In *Mining with Backfill*; 12th Canadian Rock Mechanics Symposium; CIM Special Volume 19; 1978.

7. Higgins, L.M. and Bauer, W.H. "Utilization of lead and zinc slags in ceramic construction products"; In *Conservation and Recycling* 3:375-382; Pergamon Press, London; 1980.

8. Ovcharenko, G.I.; Gregouer, B.A.; Gorbunova, N.E.; Mosiondz, K. "Possibility of using Cu-Ni industrial slags for the production of structural materials" (in Russian); Stroit, Maten Poputnikh Prod. Prom-sti 105-10; CA 92; 1978.

9. ASTM standards; C 593; 1983.

10. Douglas, E.; Malhotra, V.M.; and Emery, J.J. "Cementitious properties of non-ferrous slags from Canadian sources"; *Cement, Concrete and Aggregates*; ASTM; Vol. 7, No. 1; Summer 1985.

11. Douglas, E.; Mainwaring, P.R; and Hemmings, R. "Pozzolanic properties of Canadian non-ferrous slags"; *Proceedings*, 2nd International Conference on the use of fly ash, silica fume, slag and natural pozzolans in concrete; CANMET and ACI; April 21 to 25; Madrid, Spain; 1986.

12. McGuire, A.J. "Falconbridge slag as a cementing agent in backfill"; In *Mining with Backfill*; 12th Canadian Rock Mechanics Symposium; CIM Special Volume 19; 1978.

13. Roy, N.N. "Method for determination of glass content in quenched slag"; Falconbridge Nickel Mines Limited Canada, *Internal Report*; 1975.

14. Hooton, D. "Pelletized slag cement: autoclave reactivity"; Ph.D. thesis; McMaster University; 1981.

15. Douglas, E. and Mainwaring, P.R. "Hydration and pozzolanic activity of non-ferrous slags"; American Ceramic Society Bulletin; Vol. 64, No. 5; May 1985.

16. Roper, H.; Kam, F; and Auld, G. "Characterization of a copper slag used in mine fill operations"; *Proceedings* 1st Int Conference on the use of fly ash, silica fume, slag and other mineral by-products in concrete; Montebello, Québec; July 31-August 1; 1983.

17. Landriault, D., Personal Communication; INCO Mines Ltd.; Sudbury, Ont.; 1983.

18. Thomas, E.G. "Minimization of contamination of mine ore by cemented hydraulic fill"; *Proc Aust Inst Min Met* 251; 1974.

19. Douglas, E. "Characterization of non-ferrous slags from Canadian sources; Part I – Hydration of cementitious materials with special reference to non-ferrous slags"; *Division Report* ERP/MSL 83-81(LS); CANMET, Energy, Mines and Resources Canada; 1983.

20. Barsotti, C. "The evaluation of fill mining at the Ontario Division of Inco Metals"; In *Mining with Backfill*, 12th Canadian Rock Mechanics Symposium; Special Volume 19; 1978.

21. Emery, J.J. "Characterization of non-ferrous slags from Canadian sources"; Report on Contract No. 26SQ.23440-2-9095; Mineral Sciences Laboratories; CANMET, Energy, Mines and Resources Canada; November 1984.

22. Midgley, H.G. "The formation and phase composition of portland cement clinker"; In *The Chemistry of Cement*; Vol. 1; H.F.W. Taylor, Editor; Academic Press; London, England; 1964.

23. Turriziani, R. "Aspects of the chemistry of pozzolans"; In *The Chemistry of Cements*; Vol. 2; H.F.W. Taylor; Editor; Academic Press; London, England; 1964.

24. Fournier, M. and Geoffray, J.M. "Le liant pouzzolanes-chaux"; Bull Liaison Labo P et Ch; 93:70; 1978.

25. Millet, J.; Fournier, A.; and Sierra, R. "Rôle des chaux industrielles dans leur emploi avec les materiaux a charactère pouzzolanique"; *Silica Ind*; 41/4-5:265-252; 1976.

26. Locher, F.W. "Hydraulic properties and hydration of glasses of the system $CaO-Al_2O_3-SiO_2$"; *Proceedings* of the 4th International Symposium on the chemistry of cement; Washington, U.S.A.; 1962.

27. Sersale, R. "Structure and characterization of pozzolans and of fly-ashes"; 7th International Congress on the chemistry of cement; Paris; 1980.

28. Takemoto, K. and Uchikawa, V. "Hydration of pozzolanic cement"; 7th International Congress on the chemistry of cement; Paris; 1980.

29. Kam, F.S.Y. "Investigation of copper slag for use in mine fill"; Master's thesis; School of Civil and Mining Engineering, University of Sydney, Australia; 1984.

30. Douglas, E. and Malhotra, V.M. "Non-ferrous slags from Canadian sources. Part II – Properties and strength development"; *Division Report* ERP/MSL 84-30; CANMET, Energy, Mines and Resources Canada; 1983.

31. Douglas, E.; Malhotra V.M.; and Emery, J.J. "Characterization of non-ferrous slags from Canadian sources"; *Division Report* ERP/MSL 84-36; CANMET, Energy, Mines and Resources Canada; 1984.

32. Stutherheim, N. "Portland blast-furnace cements: A case for separate grinding of slag"; 5th International Symposium of chemistry of cement; Tokyo; 1968.

33. Thomas, E.G. "A review of cemented agents for hydraulic fill"; Austral Inst Mine Metall Jubilee Symposium on mine filling; Mount Isa; 1973.

34. Laneuville, J. "The hardening of nickel slags"; 7th Int Cong Chem Cement; Paris; 1980.

Table 1 — Chemical analysis of Canadian non-ferrous slags (wt %) (10)

	A Lead (N.B) granulated	B Nickel (Ont.) air-cooled	C Nickel (Ont.) quenched	D Copper (Ont.) granulated	E Copper (Ont.) quenched	F Copper (Que.) air-cooled	G Copper (Que.) air-cooled	H Copper (Que.) quenched	I Copper (Que.) granulated
SiO_2	19.1	35.66	37.25	26.54	22.10	36.26	34.51	36.78	34.41
Al_2O_3	1.66	5.59	6.17	3.74	2.94	2.16	6.55	7.16	6.82
Fe_2O_3*	45.35	52.99	53.07	60.07	44.36	49.00	49.50	50.00	49.64
CaO	16.60	2.74	2.97	2.09	20.32	7.30	2.20	1.93	1.66
MgO	0.68	2.53	2.43	1.63	1.52	1.91	1.48	1.49	1.91
Na_2O	0.26	0.87	0.86	0.39	0.23	0.28	1.02	1.06	1.34
K_2O	0.25	0.65	0.62	0.33	0.98	1.26	1.01	0.96	0.66
TiO_2	0.14	0.32	0.33	0.14	0.12	0.13	0.35	0.39	0.28
MnO	0.09	0.07	0.07	0.10	0.08	0.08	0.10	0.09	0.08
Cu	—	—	—	1.10	—	0.48	0.43	0.41	0.48
Ni	—	0.23	0.25	—	—	—	—	—	—
Pb	4.84	—	—	—	—	—	—	—	—
LOI**	−5.75	−5.32	−6.00	−5.84	−4.39	−3.91	−5.24	−6.13	−4.73
S	1.30	1.46	1.39	1.28	0.45	1.01	1.20	1.13	1.00

*Total iron expressed as Fe_2O_3.

**LOI at 700°C. Negative values indicate a gain after ignition caused by oxidation of FeO and S^2.

Table 2 — Bulk composition of Canadian non-ferrous slags (wt %)

Element	J	I	C,D	G,H
FeO	55.1	44.6	50.3	40.9
CaO	2.1	16.7	3.5	17.6
ZnO	6.2	3.9	—	12.3
MgO	1.8	1.8	2.5	—
Al_2O_3	4.2	4.2	5.9	1.5
K_2O	0.4	0.4	0.7	0.2
CuO	—	—	—	0.1
PbO	—	—	—	3.0
TiO_2	—	—	0.3	—
SiO_2	32.1	30.6	36.6	23.5
S	0.8(s)	0.6(s)	1.5(s)	1.6(s)
Totals	101.9	102.8	101.3	100.7

n.d. = not detected (by E.D.X.A.).

S as sulphur only, not as SO_3 in oxide wt % column.

Table 3 — Copper slag* constituents determined by image analysis (15)

Sample	Fields	R**	Glass	Fayalite	Spinel	Sulphide
G,GB, Air-cooled	30	1.5	41±4	57±6	5±1	0.2
H,HA, Quenched	20	0.3-0.1	75-95	15-5	10-trace	—

*From Quebec.

**Ratio of crystals to glass.

Table 4 — Compositions of glass determined by electron microprobe in copper slags (Quebec)

	A Air-cooled slag	B Quenched slag
MgO	—	1.4 ± 0.03
Al_2O_3	14.5 ± 0.2	10.1 ± 0.2
SiO_2	45.8 ± 0.8	38.6 ± 0.5
K_2O	2.1 ± 0.2	0.6 ± 0.03
CaO	3.6 ± 0.7	1.7 ± 0.04
MnO	0.1 ± 0.02	0.1 ± 0.03
Fe_2O_3*	28.7 ± 3.8	39.4 ± 0.6
ZnO	5.3 ± 0.7	5.0 ± 0.2
PbO*	0.8 ± 0.1	0.4 ± 0.1
Total	100.9	101.4

*Total Fe calculated as Fe_2O_3.

Table 5 — Estimated kWh/t required to grind nickel slag (Ontario), calculated from grinding times (15)

	Air-cooled #1	Air-cooled #2	Granulated
Fineness (cm^2/g, Blaine method)			
3000	50	58	88
3500	65	65	107
3800	77	77	117
4000	83	83	128

Table 6 — Particle-size distribution of granulated nickel slag (Ontario) ground to 3000 cm²/g (12)

Particle size (micrometres)	Weight Percentage	
	Slag	Fill
+ 208	0.5	9.5
+1147	0.5	17.2
+ 104	0.7	16.7
+ 74	2.4	16.3
+ 53	9.7	11.3
+ 38	10.7	15.9
+ 27	29.7	12.2
+ 19	9.7	0.4
+ 13	9.9	0.2
+ 9	6.9	0.1
+ 7	4.42	0.06
+ 5	4.97	0.05
+ 3	4.97	0.05
+ 2	3.38	0.03
− 2	1.36	0.01

Table 7 — Size distribution, surface area, and specific gravity of ground nickel slags (Ontario) tested for pozzolanic activity (17)

(a) Size Distribution Microns	CC Dump**	
	Wt %	Cum Wt
+74	0.09	0.09
45	0.14	0.23
37	0.09	0.32
23	2.57	2.89
17	12.88	15.77
13	14.08	29.85
−13	70.15	100.00

(b) Surface Area	S.A. (cm²)
Blaine (cm²/g)	4437
B.E.T. (m²/g) (Gas adsorption)	20.9
Specific gravity	3.30

**CC dump slag stands for Copper Cliff dump slag.

Table 8 — Energy consumption for grinding non-ferrous slags (10)

Sample	Average fineness measured cm²/g				Grinding time min				Energy consumed kWh/t				Specific gravity* cm²/g	% passing 45 μm			
	a	b	c	d	a	b	c	d	a	b	c	d		a	b	c	d
A	2029	2970	3891	5012	75	180	653	1335	30	72	261	534	4.00	76.52	85.55	87.59	88.52
B	2080	3044	4047	5026	50	75	115	178	20	30	46	71	3.54	70.57	83.68	91.49	94.59
C	2025	3098	3935	5019	60	75	120	210	24	30	48	84	3.45	69.49	86.94	91.32	95.16
D	2012	2976	4014	—	95	195	600	—	38	78	240	—	3.90	69.04	79.48	80.92	—
E	1995	3168	4095	4923	55	140	210	365	22	56	84	146	3.68	59.65	—	91.36	95.31
F	2034	3104	3955	4966	50	120	190	285	20	48	76	114	3.73	56.63	82.80	87.50	92.49
G	1979	3107	3927	4999	50	118	190	325	20	47	76	130	3.53	59.84	77.36	82.61	88.63
H	1985	3150	4138	4936	63	122	240	360	25	49	96	144	3.39	62.34	90.41	92.23	92.61
I	1987	2999	4049	5087	70	103	190	280	28	41	76	112	3.50	68.04	85.42	91.68	93.09
J	2032	2981	4118	4983	55	105	240	360	22	42	96	144	3.40	49.39	89.97	93.88	94.92
K	1975	2975	3968	—	70	240	600	—	28	96	150	—	3.58	63.12	71.77	73.82	—
L	1951	3031	3985	5038	65	140	240	420	26	156	96	168	3.40	66.04	92.42	93.79	94.47

Note: a, b, c, d indicate slags ground to 2000, 3000, 4000, and 5000 cm²/g, respectively.

*Specific gravity determined in samples ground to 4000 cm²/g.

Table 9 — Grinding energy requirements and compositional characteristics of non-ferrous slags* (10)

Slag**	kWh/t	−75 μm %	SiO_2 %	Fe_2O_3 %	Vitrification***
B	46	8	35.7	53.0	crystalline
C	48	1	37.2	53.1	glassy/crystalline
F	76	2	36.3	49.0	crystalline
G	76	3	34.5	49.5	crystalline
I	76	1	34.4	49.6	glassy/crystalline
E	84	0.9	22.1	44.4	glassy/crystalline
H	96	0.5	36.8	50.0	very glassy
J	96	4	42.8	45.8	glassy
L (3000 Blaine 96)	150	0.3	27.2	28.5	very glassy
D (3000 Blaine 78)	240	0.2	26.5	60.1	very glassy
A	261	2	19.9	45.4	very glassy

Note: Energy requirement for grinding portland-cement clinker is 44 MJ/t; for blast furnace slag, 48 kWh/t to 4000 Blaine.

*Slag K was not evaluated.

**Slags ground to 4000 Blaine, cm^2/g, unless indicated.

***Qualitatively estimated by X-ray diffraction.

Table 10 — Slag activity index of non-ferrous slags cured in moist room at 23°C for 50% portland-cement replacement by absolute volume (10)

Blaine fineness	Slag A		B		C		D		E		F		G		H		I		J		K	
	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28	7d	28d	7d	28d
2000	35	52	28	39	34	48	29	52	29	46	28	33	30	39	30	44	24	38	25	38	38	55
3000	40	64	28	42	35	52	33	70	35	59	35	43	30	49	40	67	27	39	28	39	46	70
4000	45	81	32	48	37	59	34	73	40	67	38	52	35	56	47	83	33	59	39	59	54	91
5000	58	78	36	68	42	71	NG	NG	51	83	41	58	36	66	55	96	37	70	42	70	NG	NG

Notes: 1. Portland cement meets the requirements of ASTM C 989, "Specification for ground blast-furnace slag for use in concrete and mortars", Table 3.
2. Nominal Blaine, cm^2/g, of slags indicated 2000, 3000, 4000 and 5000.
3. NG indicates slag was not ground to this fineness.

Table 11 — Chemical composition of air-cooled and of quenched nickel slags (Ontario) (17)

	Fe	S	SiO_2	CaO	MgO	Al_2O_3	$\%Al_2O_3 + \%CaO + \%MgO/\%SiO_2$ hydraulic modulus
Nickel reverberatory, air cooled	36.0	1.5	35.5	2.25	2.50	5.05	0.2761
Nickel reverberatory, water quenched	35.8	1.4	36.8	2.30	2.45	5.55	0.2799
Flash furnace slag, air cooled	35.8	1.5	30.8	7.00	2.45	6.00	0.5016
Flash furnace slag, water quenched	34.4	1.4	31.0	7.05	2.50	6.50	0.5177
Nickel reverb. +14% limestone, water quenched	32.9	1.4	32.8	9.40	2.45	5.85	0.5396
Ground quartz	0.58	—	87.7	0.27	0.029	1.10	0.0160

Table 12 — Composition of the specimens incorporating air-cooled and quenched nickel slags (Ontario) (17)

Series No.	1	2	3	4	5	6	7
Description							
Wt % slag	0	0	1.2	4.5	4.5	8.7	16.0
Wt % cement	9.1	4.8	4.7	4.6	4.5	4.4	4.0
Wt % tailings	90.9	95.2	94.1	93.1	91.0	86.9	80.0
Total wt % binders	9.1	4.8	5.9	6.9	9.0	13.1	20.0
% cement replacement	0	0	20	33	50	66	80
Tailings/cement/slag	10:1:0	20:1:0	20:1:25	20:1:50	20:1:1	20:1:2	20:1:4

Table 13 — Pozzolanic and slag activity indexes of portland cement-slag (Quebec) mortars cured at room temperature (21)

PI/HI*	Copper air-cooled	Copper quenched
2000	0.71/0.32	0.67/0.31
3000	0.73/0.36	0.87/0.27
4000	0.89/0.49	0.85/0.70
5000	0.91/0.38	1.06/0.52

*PI:pozzolanic index; HI:slag activity index (hydraulic index).

Table 14 — Pozzolanic and hydraulic indexes of Canadian non-ferrous slags (ASTM C 595) (21)

PI/HI	Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
2000	0.50/0.25	0.64/0.40	0.55/0.26	0.48/0.24	0.57/0.33	0.49/0.24	0.58/0.39	0.51/0.32	0.56/0.32
3000	0.54/0.27	0.73/0.43	0.67/0.41	0.69/0.29	0.72/0.43	0.67/0.35	0.80/0.49	0.73/0.42	0.70/0.40
4000	0.96/0.29	0.83/0.58	0.78/0.44	0.69/0.31	0.76/0.45	0.70/0.47	0.85/0.59	0.80/0.54	0.79/0.50
5000	1.01/0.36	0.98/0.67	0.88/0.57	NG	0.81/0.52	0.83/0.53	1.02/0.71	0.85/0.69	0.83/0.64

Notes: 1. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
2. NG indicates slag was not ground to this fineness.
3. PI and HI are the pozzolanic (pozzolanic activity index) and hydraulic (slag activity index), indexes with lime and cement, respectively, in accordance with ASTM C 595.

Table 15 — Relative strength of portland cement-nickel slag mortars showing the effect of fineness (5)

Slag fineness (cm^2/g)	Curing age days	Relative strength (%)
3000 (granulated)	3	63
	7	66
	28	81
4000 (air-cooled)	3	60
	7	72
	28	78
7700 (air-cooled)	3	68
	7	75
	28	90

Table 16 — Uniaxial compressive strength of ground copper reverberatory furnace slag and $Ca(OH)_2$ pastes (29) (Water/solids ratio = 0.30)

CRFS*:$CA(OH)_2$	Strength (MPa)	Mean (MPa)	Standard deviation (MPa)
1:1	6.632	5.851	1.842
	3.314		
	5.834		
	7.622		
2:1	4.678	4.686	0.143
	4.882		
	4.540		
	4.642		

*CRFS: copper reverberatory furnace slag.

Table 17 — Effect of density and water content on compressive strength of fill at an early age (24)

Dry density (g/cm^3)	Water content (g)	Strength (MPa)
2.21	29.7	2.028
2.10	12.3	1.596
2.10	15.2	1.331
2.18	13.5	1.852
2.17	12.6	1.869
1.96	16.3	0.926
2.13	13.8	1.719
2.23	11.9	1.772
2.15	13.3	1.640
2.18	12.6	1.940
2.20	13.2	2.134
2.10	15.5	1.667

Table 18 — Mix proportions for cemented-mine tailings and compressive strength development (21)

Mix	Mix No. 1 slag	Mix No. 2 slag	Mix No. 3 slag
Compressive Strengths, MPa			
7 days (strength not adequate for testing)	—	—	—
28 days	2.2	2.3	2.5
	2.1	2.1	2.4
	1.9	2.3	2.5
Average	2.1	2.2	2.5
90 days	1.63	1.62	1.66
	1.66	1.68	1.68
	1.59	1.67	1.69
Average	1.63	1.66	1.68
Slag 4000 Blaine, kg	0.100	0.232	0.300
Type 10 cement, kg	0.100	0.116	0.100
NRT tailings, kg	2.300	2.552	2.100
Water, kg	0.750	0.870	0.750

Note: Absolute volume replacement not adopted.

Mix No. 1: 4% slag 4000 Blaine and 4% Type 10 portland cement.
Mix No. 2: 8% slag 4000 Blaine and 4% Type 10 portland cement.
Mix No. 3: 12% slag 4000 Blaine and 4% Type 10 portland cement.

Table 19 — Cemented rockfill mix proportions and compressive strength development of rockfill (21)

Compressive Strengths	
7 days (Strength not adequate for testing)	
28 days	1.04
	1.14
	0.88
Average	1.02
90 days	1.59
	1.88
	1.72
Average	1.73
Mix	
KCCG 3000, kg	3.27
ASTM Type 10 cement, kg	2.18
Fine rockfill, kg	27.27
Coarse rockfill, kg	81.82
Water, kg	5.46

Notes: 1. Some places of segregation observed for test cylinders.
2. Absolute volume replacement not adopted.

Table 20 — Compressive strength at 28 days of mortar cubes cured at 38°C with 20, 35, 50, and 70% absolute replacement of portland cement by slag (21)

	Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
CONTROL	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
20%									
2000 MPa	21.4	22.5	17.1	16.0	20.7	20.8	21.7	19.3	20.2
3000	22.7	24.0	20.9	23.4	23.6	22.1	25.2	23.9	20.6
4000	30.5	24.8	23.8	25.4	25.8	24.6	26.5	25.7	24.6
5000	32.3	30.2	26.3	NG	27.5	25.0	30.8	27.6	26.2
35%									
2000 MPa	14.7	18.9	16.4	14.2	17.0	14.6	17.2	15.1	16.6
3000	16.1	21.5	19.7	20.4	21.3	19.8	23.7	21.5	20.8
4000	28.5	24.5	23.0	20.3	22.5	20.8	25.3	23.8	23.5
5000	30.0	29.1	25.9	NG	24.1	24.6	30.3	25.3	24.3
50%									
2000 MPa	13.7	18.3	13.9	9.5	13.8	11.3	14.6	13.4	13.3
3000	15.0	19.1	17.3	15.5	18.0	18.0	22.7	20.2	17.3
4000	20.6	21.4	20.9	17.8	18.8	19.7	23.9	23.6	21.3
5000	22.3	28.7	25.4	NG	19.6	23.3	26.9	24.4	22.0
70%									
2000 MPa	7.3	11.9	7.8	7.2	9.7	7.0	11.5	9.7	9.6
3000	7.9	12.8	12.1	8.5	12.8	10.5	14.5	12.5	11.7
4000	8.5	17.1	13.0	9.1	13.4	13.9	17.5	16.0	14.7
5000	10.8	19.8	16.8	NG	15.5	15.6	21.0	20.4	18.8

Notes: 1. Portland cement meets requirements of CSA Type 10.
2. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
3. All compressive strengths in MPa.
4. NG indicates slag was not ground to this fineness.

Table 21 — Compressive strength at 23°C of mortar cubes with 50% absolute volume replacement of portland cement by slag (21)

		Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
CONTROL	7D	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3
	28D	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
2000										
days	1 MPa	7.0	3.9	4.8	4.6	4.7	3.1	3.3	4.3	3.8
	7	10.8	8.7	10.7	9.0	9.1	8.8	9.2	9.3	7.4
	28	19.1	14.2	17.8	19.0	17.0	12.0	14.4	16.2	13.8
	90	29.5	21.6	23.0	25.1	21.7	16.7	19.4	21.1	18.5
3000										
days	1 MPa	8.5	4.0	5.0	4.9	5.0	4.7	3.3	5.0	4.0
	7	12.4	8.8	10.8	10.3	11.0	10.9	9.5	12.6	8.6
	28	23.5	15.6	19.3	25.7	21.8	15.7	18.0	24.6	14.3
	90	37.9	26.0	26.1	29.7	26.5	20.6	25.9	32.0	24.3
4000										
days	1 MPa	12.1	4.1	5.2	5.6	6.3	5.0	4.3	5.6	4.7
	7	14.1	10.0	11.7	10.5	12.5	12.0	11.0	14.8	10.3
	28	29.8	17.5	21.7	26.7	24.8	19.2	20.5	30.5	21.6
	90	40.2	28.3	26.6	31.4	31.1	23.2	29.2	37.3	29.1
5000										
days	1 MPa	14.1	4.4	7.0	NG	7.5	5.1	4.5	5.9	5.3
	7	18.2	11.2	13.1		16.0	12.9	11.2	17.1	11.5
	28	28.7	25.0	26.2		30.4	21.3	24.2	35.2	25.9
	90	43.7	33.1	31.7		38.9	26.8	32.0	38.3	32.8

Notes: 1. Portland cement meets requirements of ASTM "Specifications for ground blast-furnace slag for use in concrete and mortars".
2. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
3. All compressive strengths in MPa, with flow indicated for each mix.
4. NG indicates slag was not ground to this fineness.

Table 22 — Gradations of coarse and fine aggregates for concrete mixes (21)

	Sieve size	Per cent passing	CSA A23.1 requirements per cent passing
Coarse aggregate	25.4 mm	100	100
	19 mm	95	90-100
	12.7 mm	52	30-75
	9.5 mm	36	20-55
	4.75 mm	2	0-10
Fine aggregate	9.5 mm	100	100
	4.75 mm	97	95-100
	2.36 mm	85	80-100
	1.18 mm	72	50-85
	600 µm	52	25-60
	300 µm	22	10-30
	150 µm	6	2-10

Table 23 — Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement (21) of CSA Type 10 portland cement

Mix	A	A	B	D	D	E	G	G	H	H	I	MICO	CONTROL	CONTROL	CONTROL
	3000	4000	3000	4000	3000	4000	3000	3000	4000	3000	4000	4000 (Foreign)	1	2	3 (Used as control)
Mix details															
Ground non-ferrous Slag, kg	8.32	8.32	7.36	7.36	8.09	8.09	7.04	7.31	7.31	4.77	4.77	6.54	—	—	—
Type 10 cement, kg	6.54	6.54	6.54	6.54	6.54	6.54	6.04	6.54	6.54	4.45	4.45	6.04	13.08	13.08	13.08
Fine aggregate, kg	38.41	38.41	38.41	38.41	38.41	38.41	35.54	38.41	38.41	26.05	26.05	35.54	38.41	38.41	38.41
Coarse aggregate, kg	52.86	52.86	52.86	52.86	52.86	52.86	48.96	52.86	52.86	35.91	35.91	48.96	52.86	52.86	52.86
Water, kg	7.28	7.28	6.82	6.82	7.17	7.17	6.41	6.80	6.80	4.50	4.50	6.18	6.46	6.46	6.46
WRA, mL	—	—	—	—	—	—	—	—	—	—	—	—	60.7 (Mulco A)	60.7 (Mulco A)	60.7 (Mulco A)
Slump, mm	130	130	75	75	110	120	50	70	100	55	50	65	45	40	70.0
Air, %	1.5	1.5	2.2	1.9	1.5	1.9	1.7	1.5	1.4	1.9	1.9	1.9	3.9	3.2	3.4
Temperature, °C	20	19	20	20	20	20	20	20	20	20	21	20	20	21	19
Bulk density, kg/m³	1937	1963	1949	1923	1958	1953	1837	1958	1968	1930	1940	1928	1928	1877	1958
Compressive strengths, MPa															
7 days	9.5	12.4	9.2	10.7	9.9	10.2	10.7	9.7	9.2	10.7	13.8	11.0	27.6	32.0	29.2
	9.3	11.9	9.2	10.2	9.4	11.1	10.5	9.6	9.2	11.0	14.0	11.2	27.3	31.0	29.8
	10.0	12.1	9.7	10.7	9.5	10.4	10.7	9.4	9.5	11.0	13.8	11.5	28.1	32.0	28.3
Average	9.6	12.1	9.4	10.5	9.6	10.6	10.6	9.6	9.3	10.9	13.9	11.2	27.7	31.6	29.1
28 days	23.7	28.5	16.6	20.1	22.4	24.7	21.4	17.3	18.4	23.4	27.5	24.5	35.6	40.8	37.4
	21.4	27.3	17.3	20.4	22.4	24.7	21.7	19.4	18.9	23.2	27.0	26.0	35.9	41.0	37.9
	21.7	30.3	16.8	20.9	21.9	26.0	21.2	18.4	18.9	24.0	26.3	24.5	—	40.5	38.1
Average	22.2	28.7	17.0	20.5	22.2	25.1	21.4	18.4	18.8	23.5	26.9	25.0	35.8	40.8	37.8
90 days	32.6	40.8	23.4	28.5	28.0	28.5	31.6	24.5	24.0	27.5	31.1	30.6	42.2	49.0	45.4
	35.6	39.7	24.0	28.0	28.0	30.1	30.1	25.5	25.0	27.5	31.2	30.1	42.3	47.3	44.2
	35.7	42.8	22.9	27.0	27.5	29.6	31.1	24.5	26.0	27.0	31.1	31.1	—	47.7	44.5
Average	34.6	41.1	23.4	27.8	27.8	29.4	30.9	24.8	25.0	27.3	31.1	30.6	42.2	48.0	44.7

Note: All mixes and test in accordance with CSA A23.1 and CSA A23.2, respectively. 100 mm Φ by 200 mm cylinders for all mixes except CONTROL 1 (150 mm Φ by 300 mm cylinders).

Table 24 — Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement of Type 10 portland cement, with water-reducing admixtures (WRA) (21)

Mix	B	B	C	C	F	G
	3000	4000			4000	3000
Mix details	WRA	WRA		WRA	WRA	WRA
Ground non-ferrous slag, kg	7.36	7.36	7.14	7.14	7.77	7.32
Type 10 cement, kg	6.54	6.54	6.54	6.54	6.54	6.54
Fine aggregate, kg	38.41	38.41	38.41	38.41	38.41	38.41
Coarse aggregate, kg	52.86	52.86	52.86	52.86	52.86	52.86
Water, kg	6.46	6.46	6.46	6.46	6.46	6.46
WRA, mL	64.5 (TCDA A)	64.5 (TCDA A)	—	63.5 (Mulco A)	66.4 (Mulco A)	64.3 (TCDA A)
Slump, mm	110	90	40	90	90	90
Air, %	4.0	3.3	2.5	5.3	3.3	3.7
Temperature, °C	21	21	20	22	21	21
Bulk, density, kg/m³	1967	1936	1954	1913	1937	1967
Compressive strengths, MPa						
7 days	12.2	12.0	14.8	14.8	15.0	11.2
	12.2	11.7	13.8	14.8	14.5	11.7
	11.7	12.4	13.8	14.0	14.8	11.7
Average	12.0	12.0	14.1	14.5	14.8	11.5
28 days	21.4	24.5	22.9	24.0	23.4	22.9
	21.9	24.5	22.4	23.2	24.0	24.0
	21.4	25.0	23.4	22.9	23.4	24.0
Average	21.6	24.7	22.9	23.9	23.6	23.6
90 days	30.6	31.1	31.1	30.1	27.8	30.6
	29.6	31.6	30.1	31.1	28.8	31.6
	29.1	21.1	20.1	31.2	28.3	31.7
Average	29.8	31.3	30.4	30.8	28.3	31.3

Note: All mixes and tests in accordance with CSA A23.1 and CSA A23.2, respectively, 100 mm Φ by 200 mm cylinders.

CANADIAN NON-FERROUS SLAGS FOR RESOURCE AND ENERGY CONSERVATION

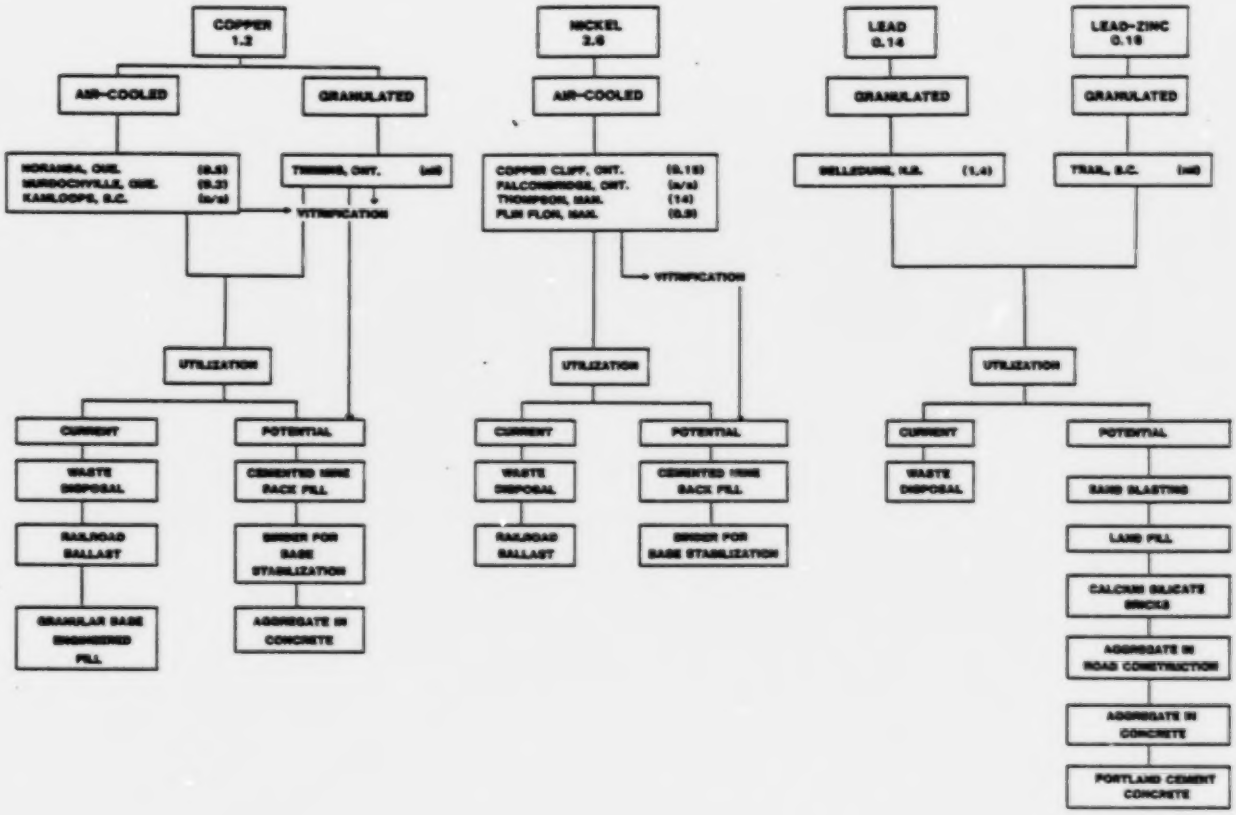


Fig. 1 — Production, location, and utilization of non-ferrous slags from Canadian sources (2)

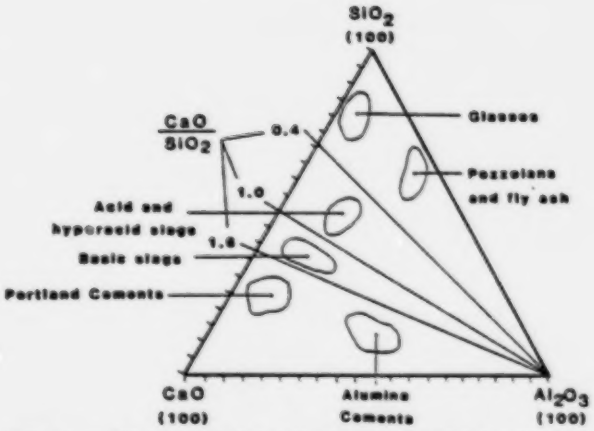


Fig. 2a — Representation of some cementitious materials in the system CaO-SiO_2-Al_2O_3

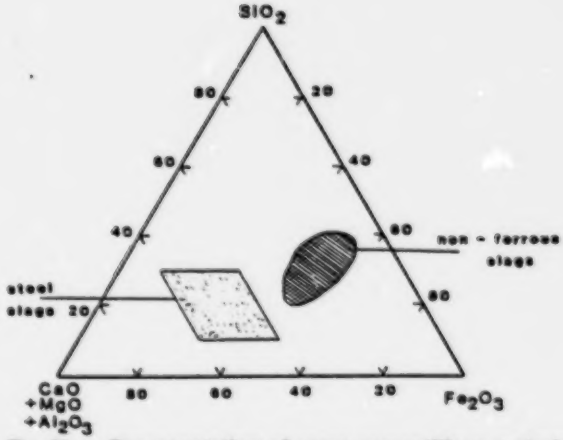


Fig. 2b — Representation of some cementitious materials in the system CaO-SiO_2-Fe_2O_3

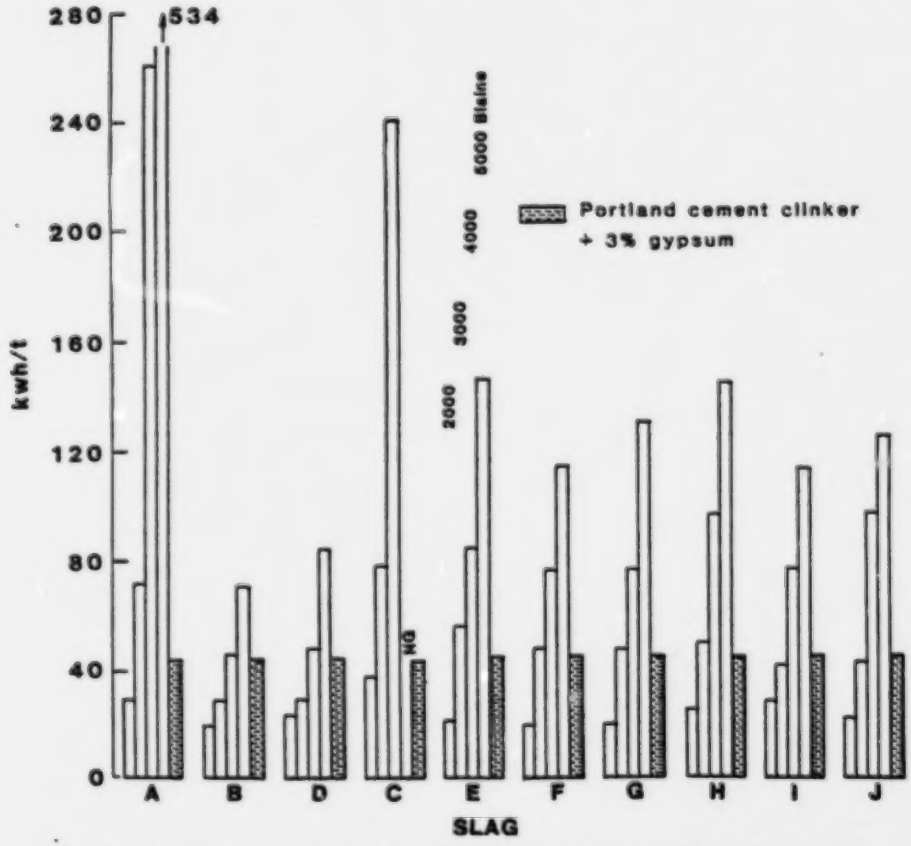
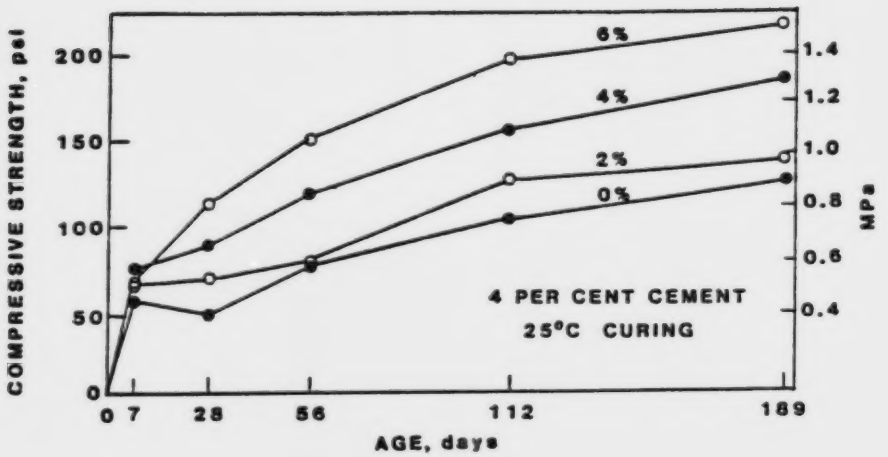
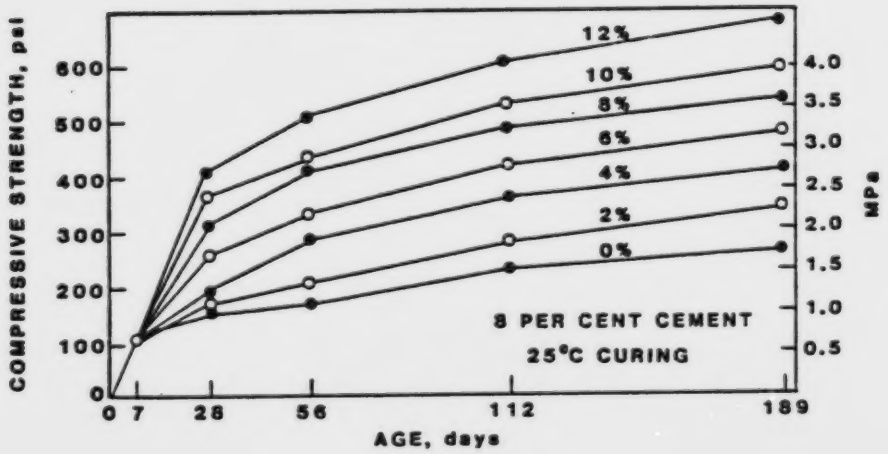


Fig. 3 — Energy consumption for production grinding of non-ferrous slags (10)





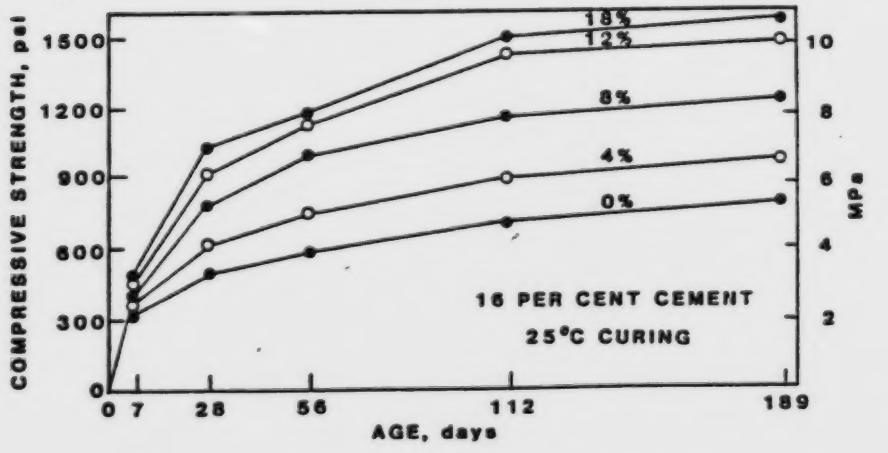


Fig. 4 — Curing curves demonstrating strengthening effect of ground copper reverberatory furnace slag acting as a pozzolan with different cement contents (3)

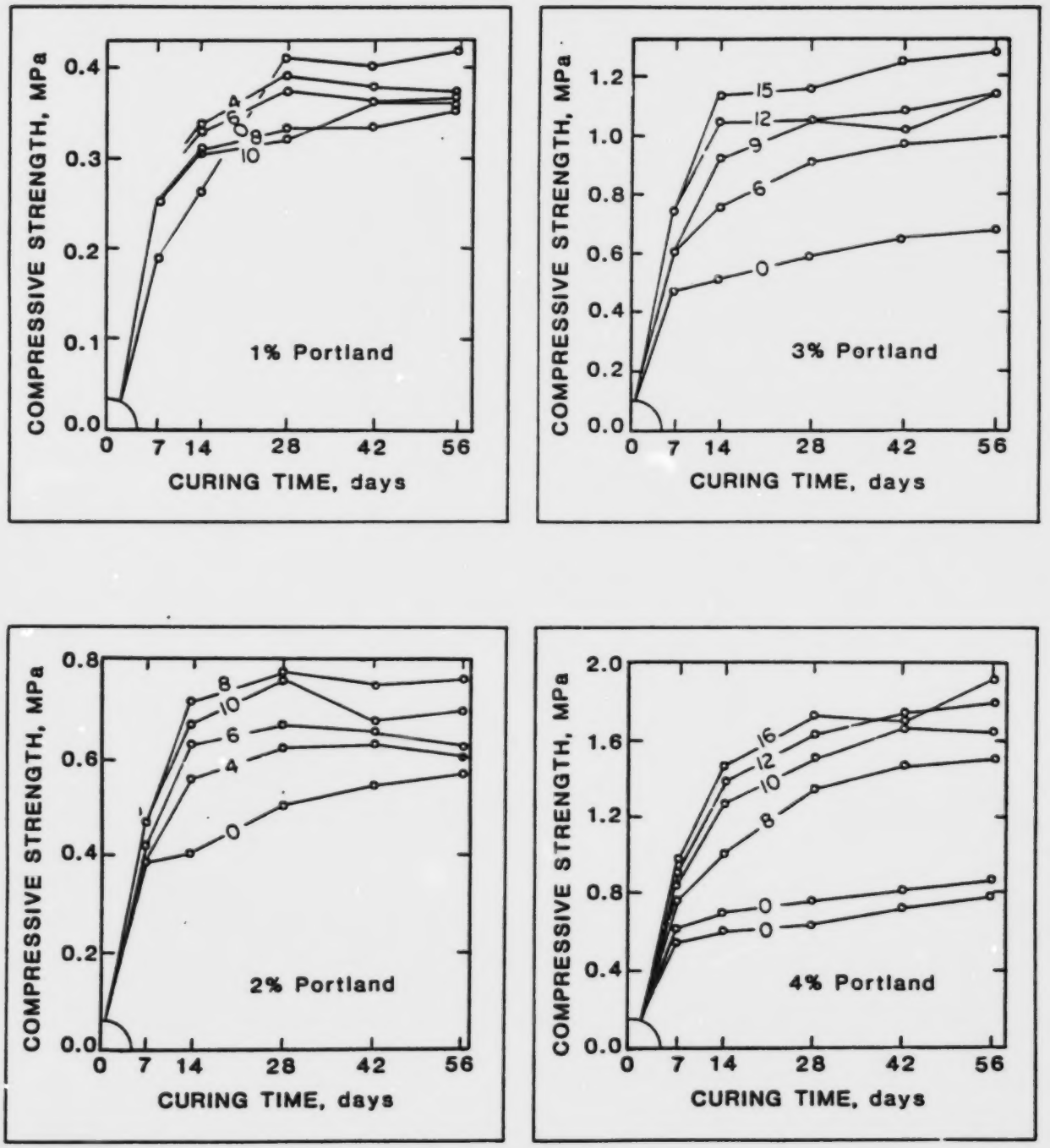


Fig. 5 — Curing curves at 1, 2, 3, and 4 wt % portland cement and various copper reverberatory furnace slag additions, as indicated on individual curves (6)

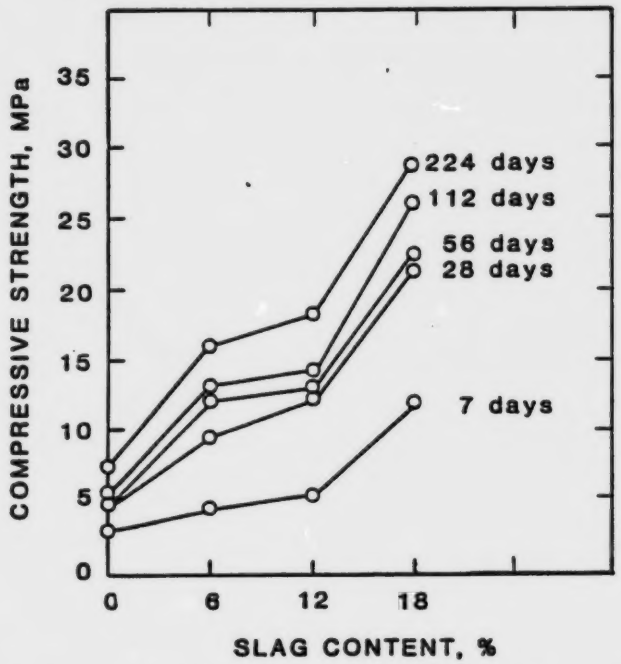


Fig. 6 — Effect of ground granulated slag on uniaxial compressive strength of consolidated fill containing 6% portland cement (12)

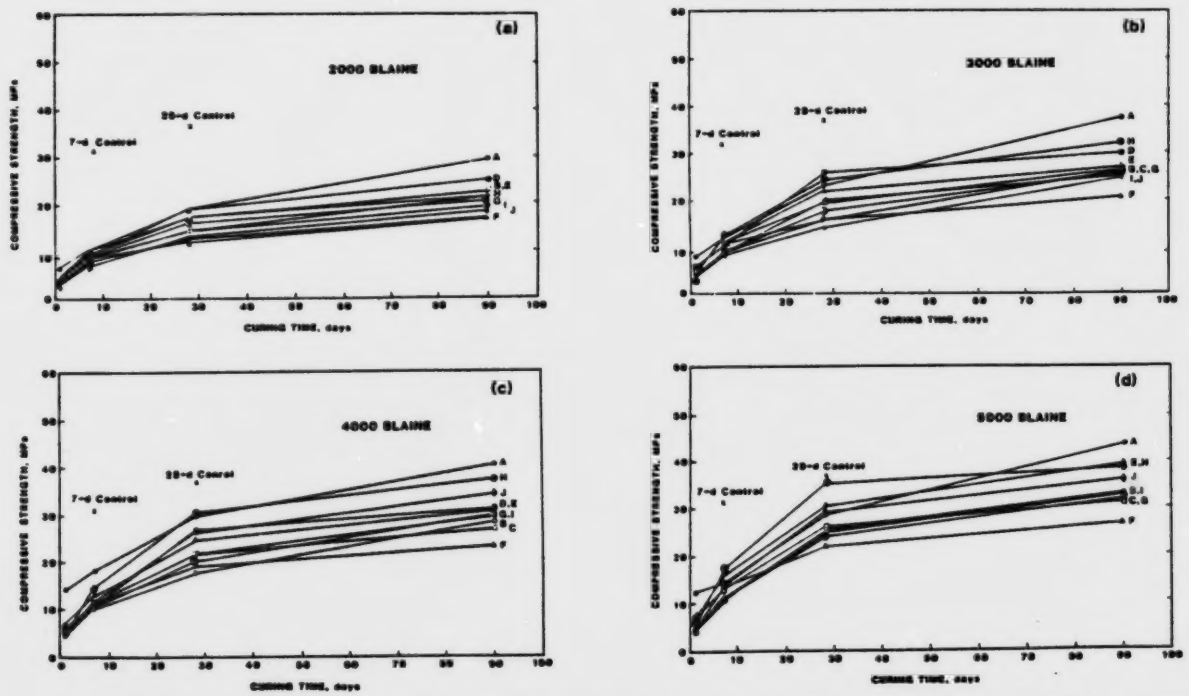


Fig. 7 — Compressive strength development at 23°C in moist-cured mortars containing 50% slag by absolute volume replacing portland cement (10)

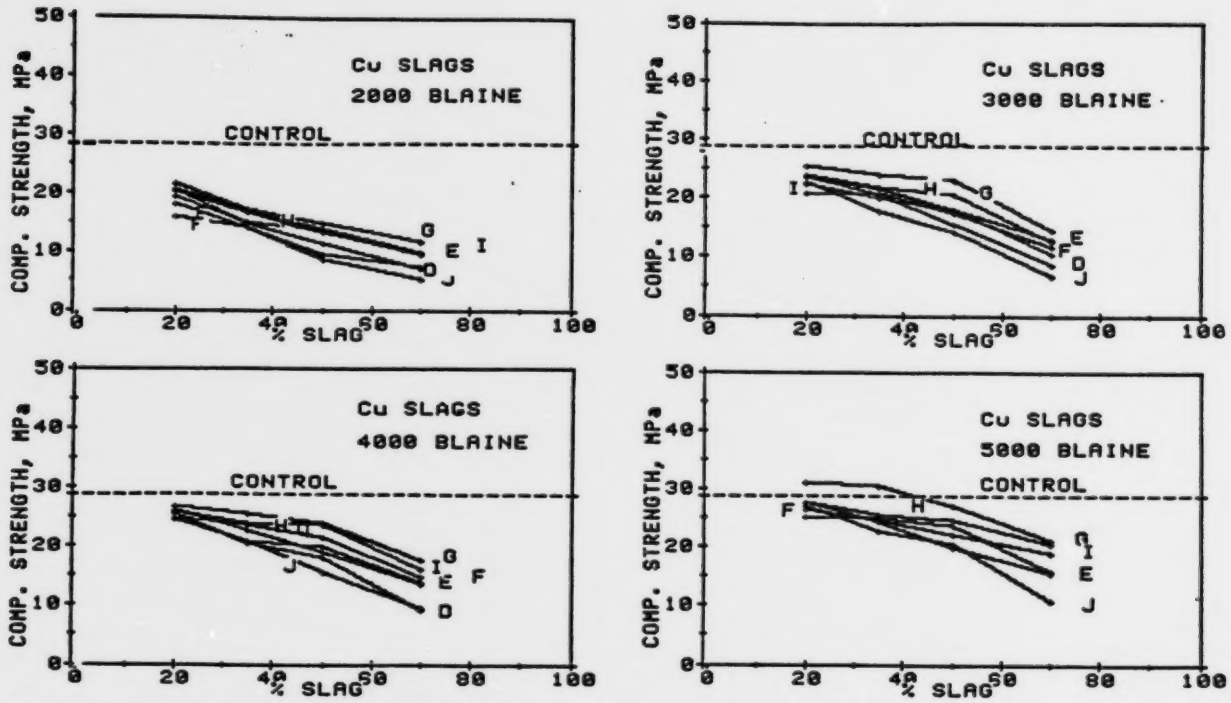


Fig. 8 — Compressive strength of copper slags-portland cement mortars at 28 days curing (10)

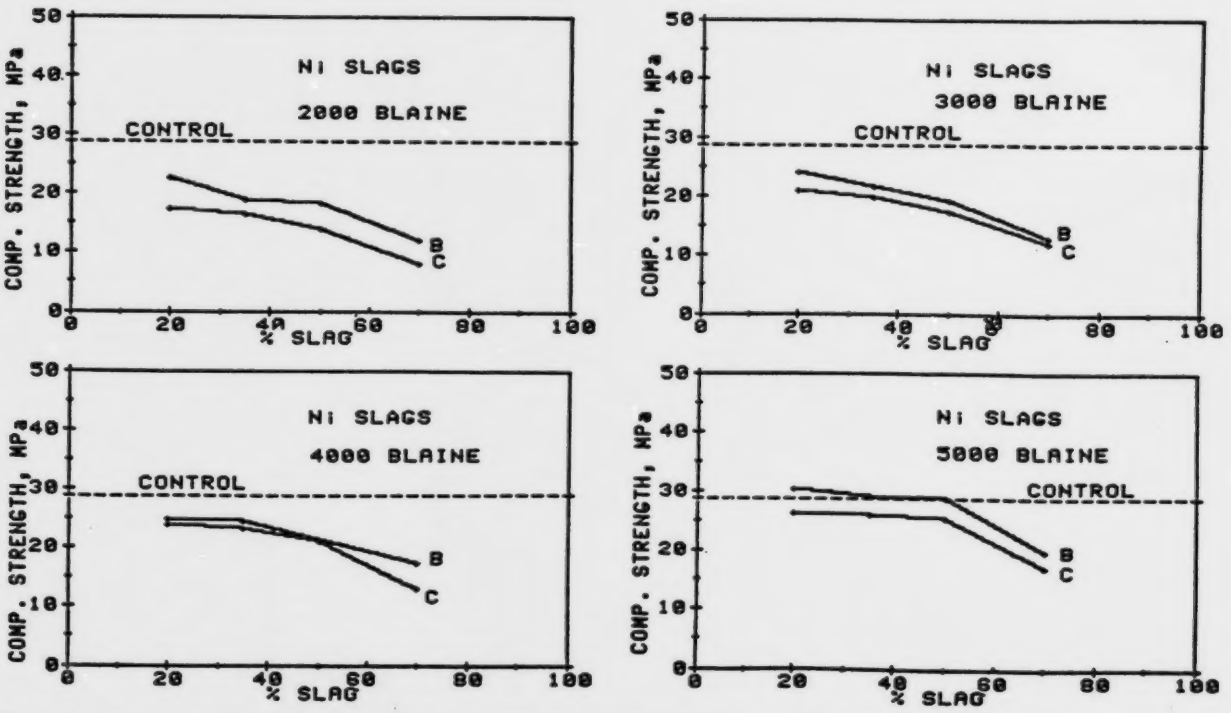


Fig. 9 — Compressive strength of nickel slags-portland cement mortars at 28 days curing (10)

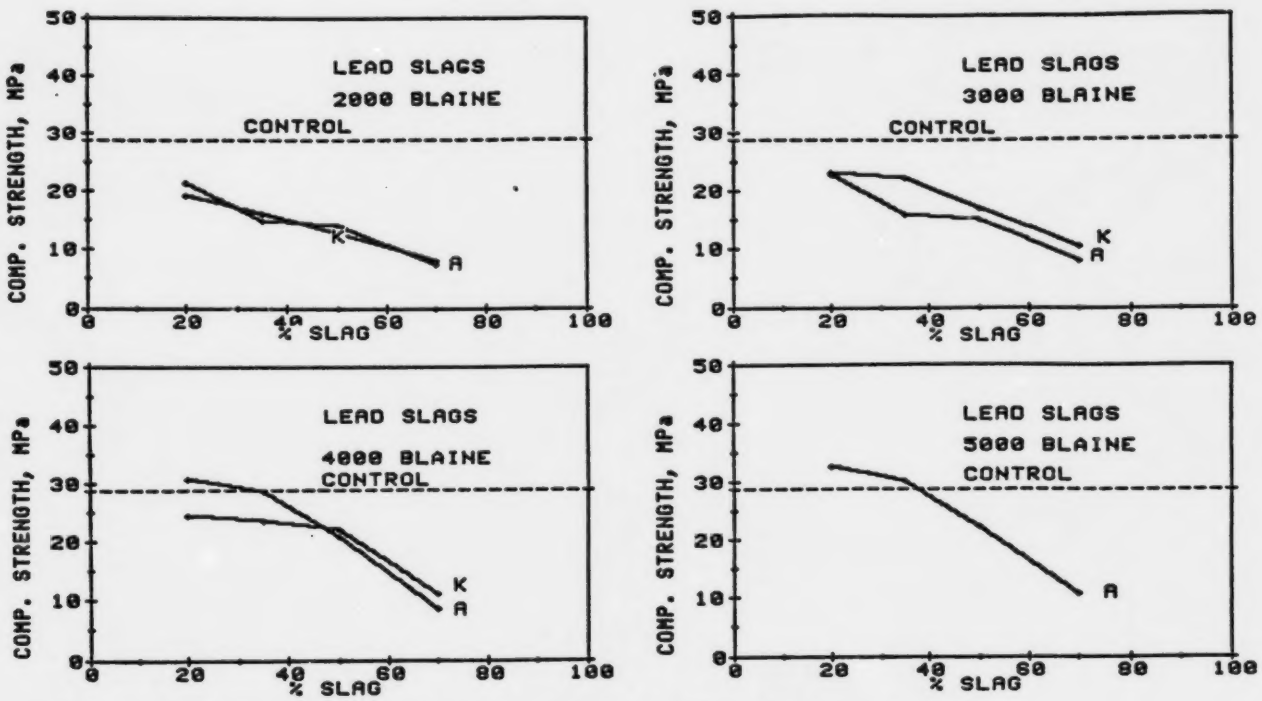


Fig. 10 — Compressive strength of lead slags-portland cement mortars at 28 days curing (10)

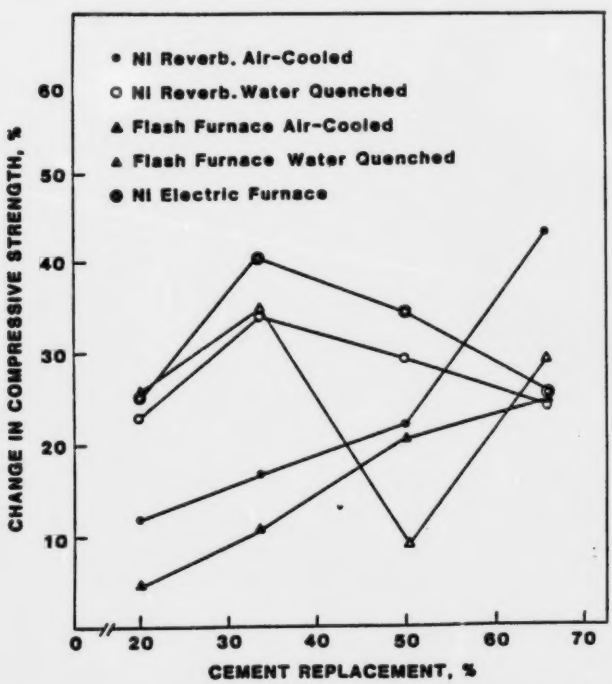


Fig. 11 — Change in strength at different curing ages calculated on basis of standard 4.8 wt % portland cement specimens cured to same age during pozzolanic testing at various cement replacement levels (20)

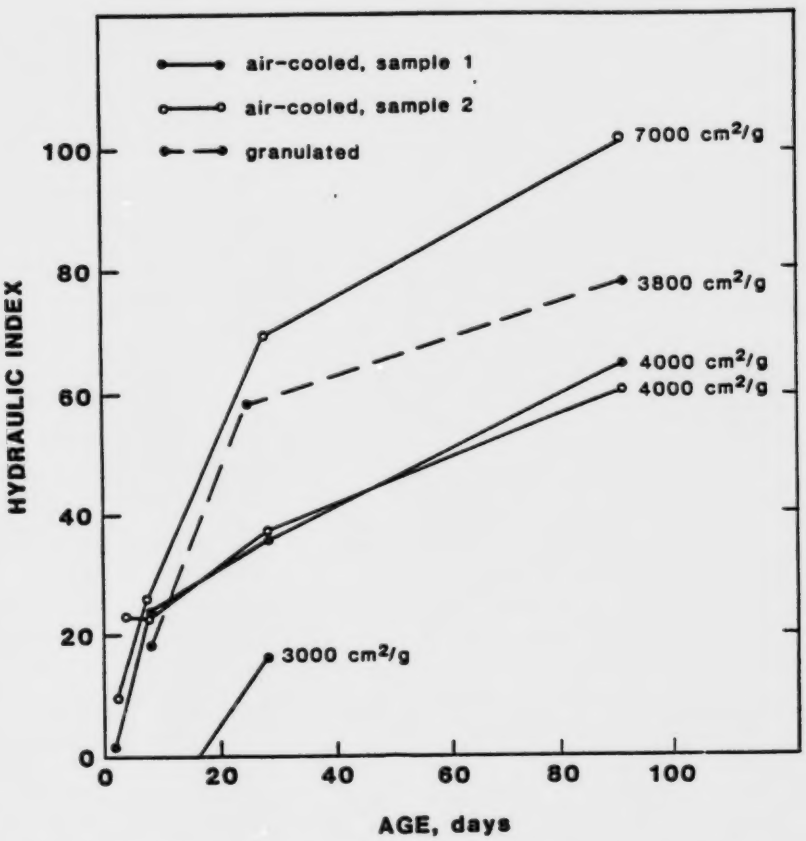


Fig. 12 — Hydraulic index of air-cooled and of granulated nickel slags of different fineness (5)

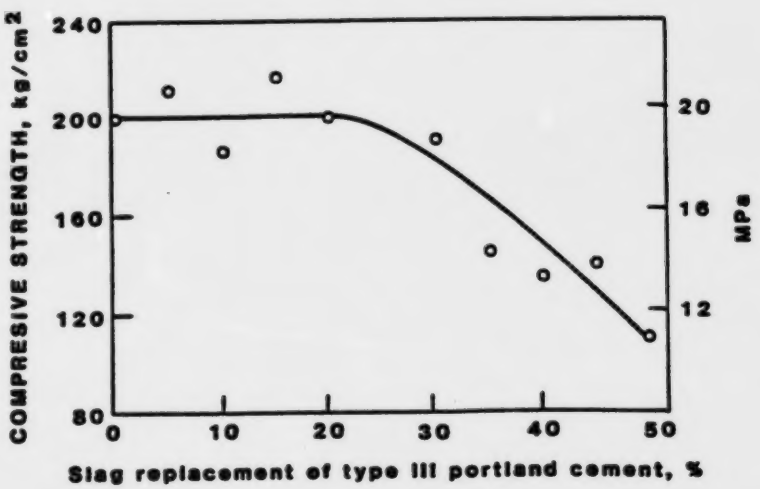


Fig. 13 — Compressive strength of Type III portland cement-lead slag binders at various cement replacement levels (7)

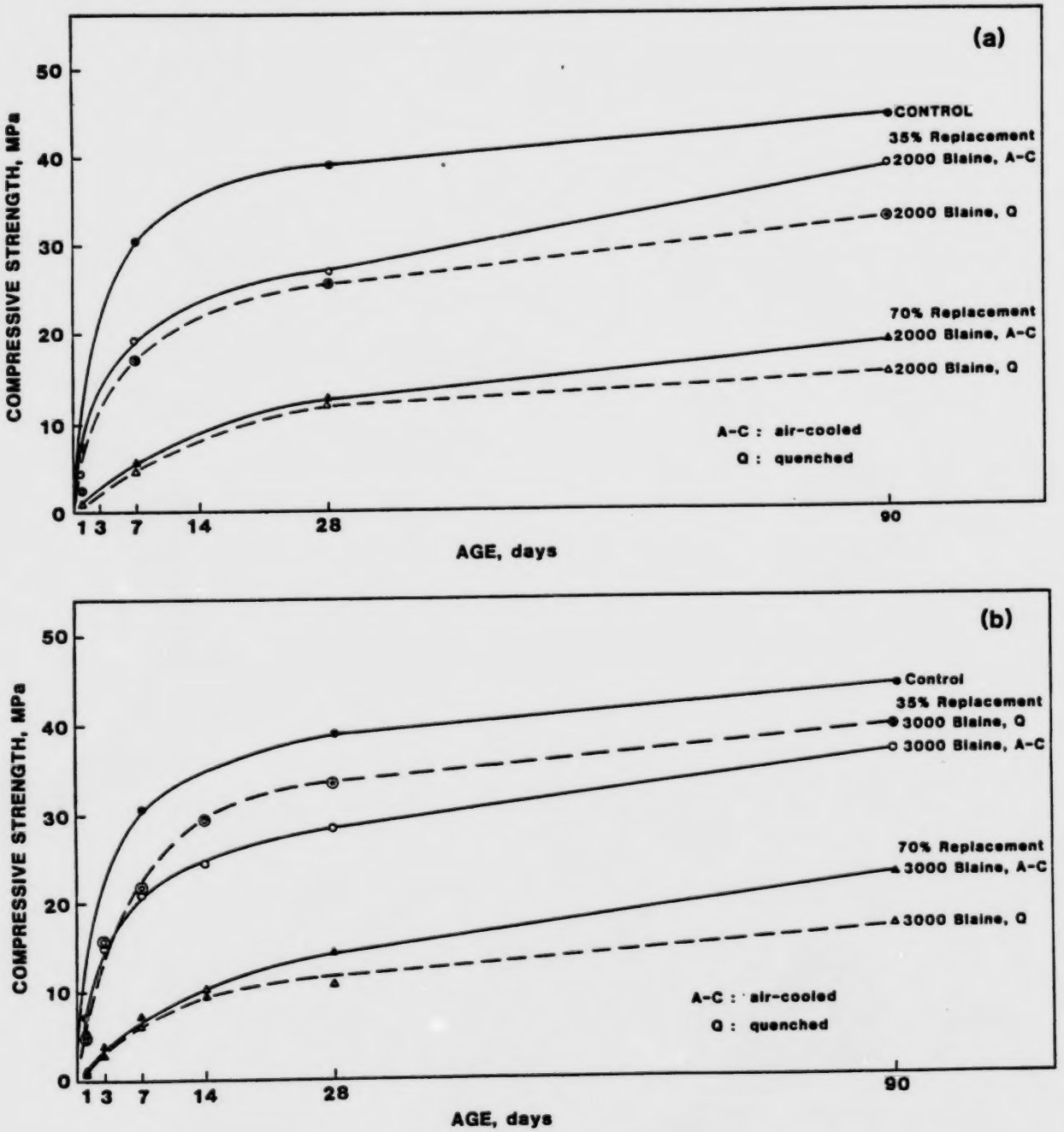


Fig. 14 — Strength development in portland cement-copper slag mortars cured at room temperature (15)

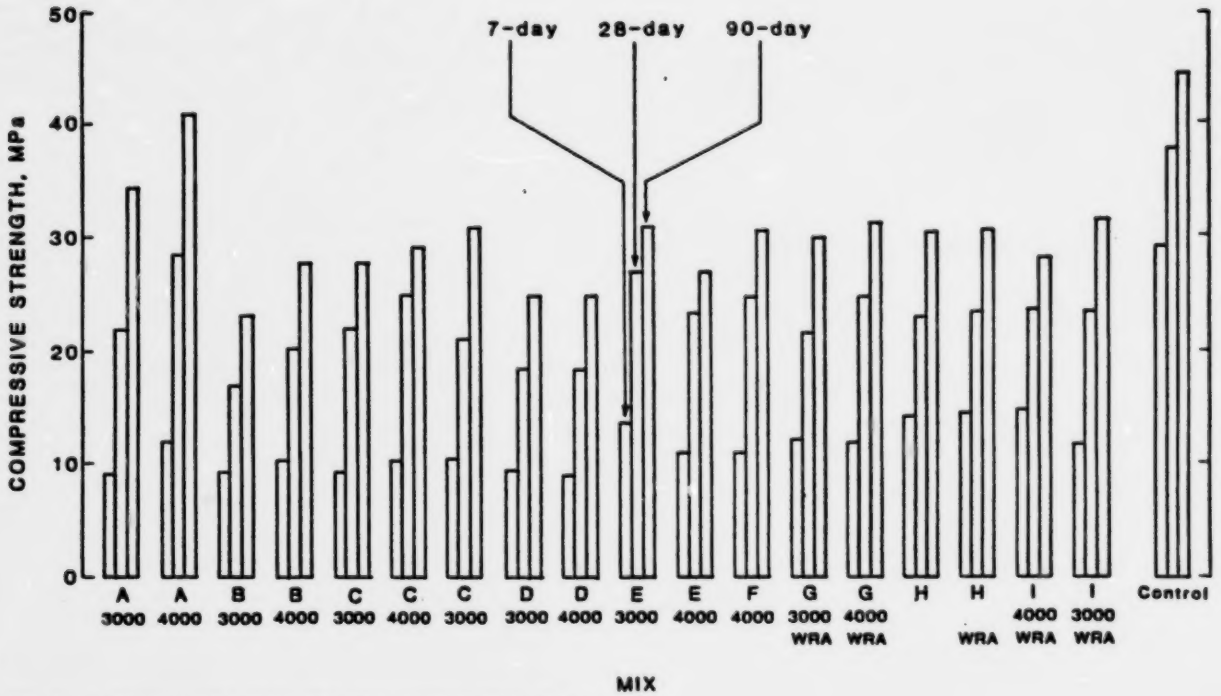


Fig. 15 — Compressive strengths of concrete mixes (21)

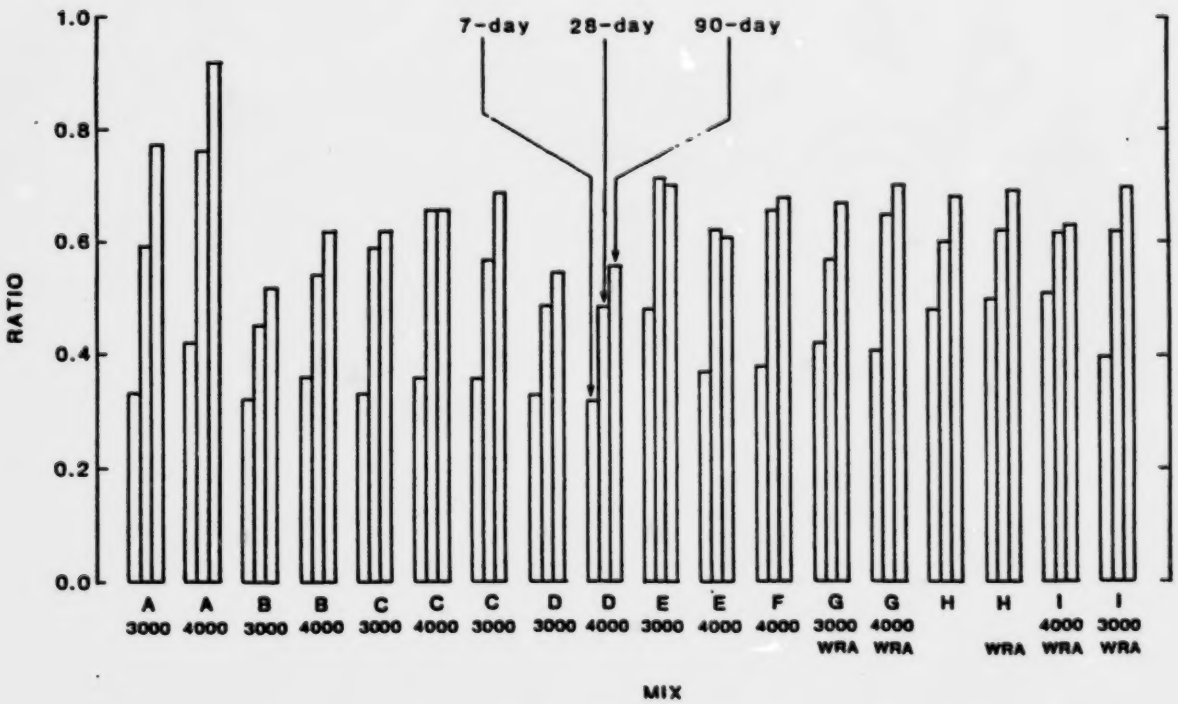
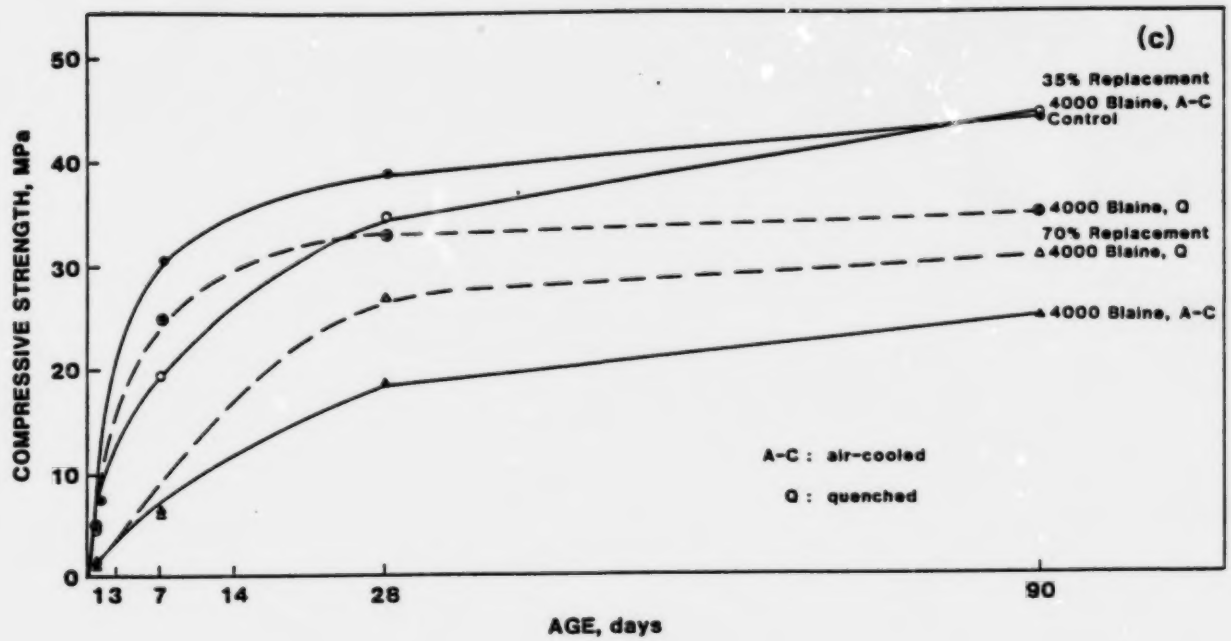


Fig. 16 — Compressive strength ratios of concrete mixes (21)



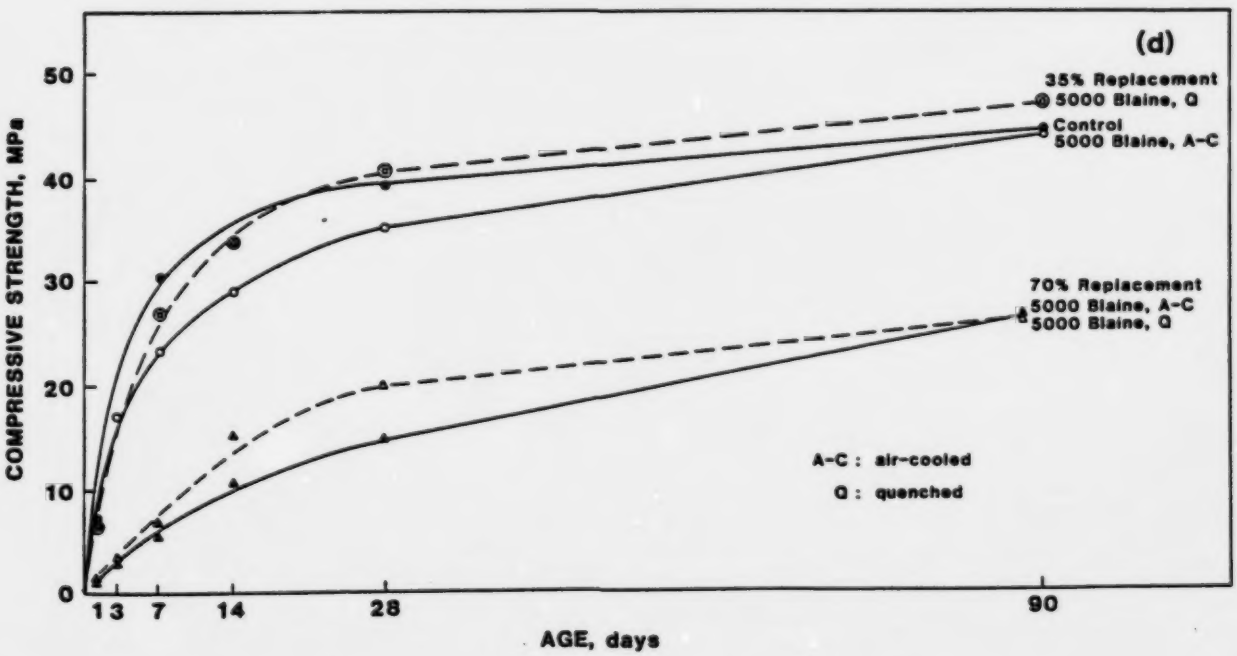


Fig. 17 — Strength development in portland cement-copper slag mortars cured at room temperature (15)
(c) slag ground to 4000 cm²/g (Blaine method)
(d) slag ground to 5000 cm²/g (Blaine method)

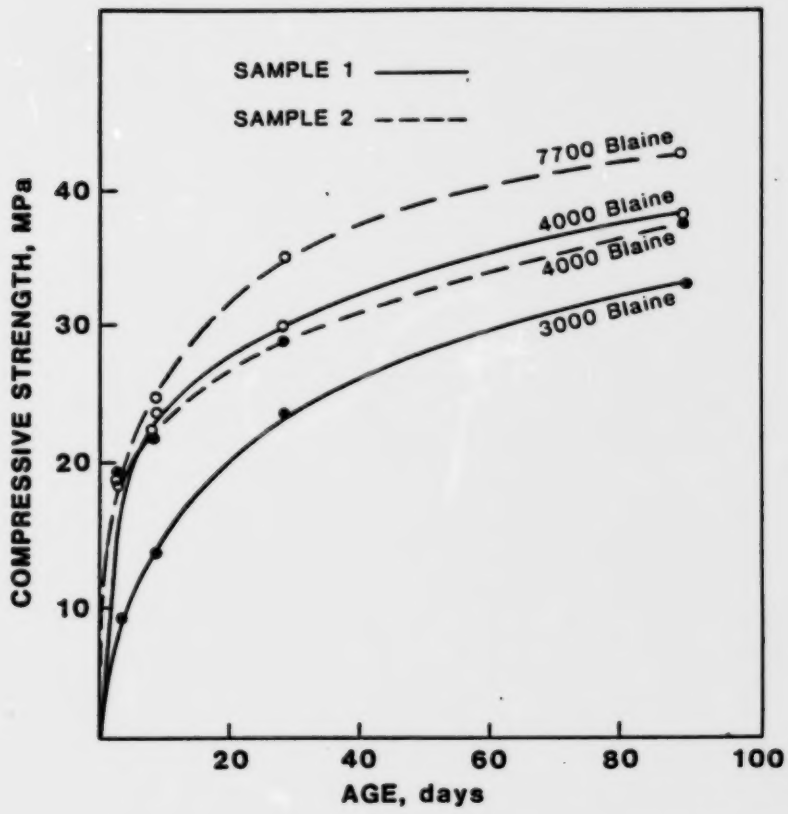


Fig. 18 — Effect of fineness on compressive strength of 70 wt % portland cement and 30 wt % air-cooled nickel slag binders (5)

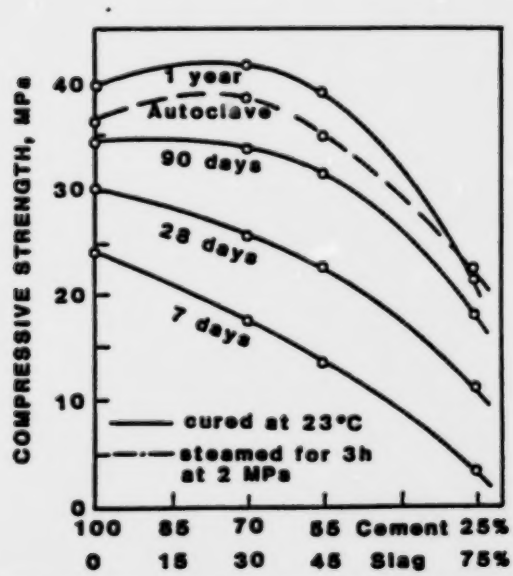


Fig. 19 — Effect of slag content of binders on compressive strength of mortar cubes (34)

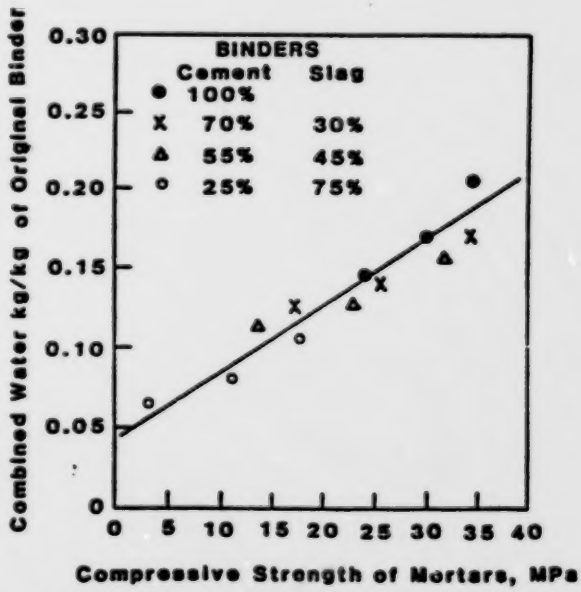


Fig. 20 — Relation between combined water and compressive strength (34)

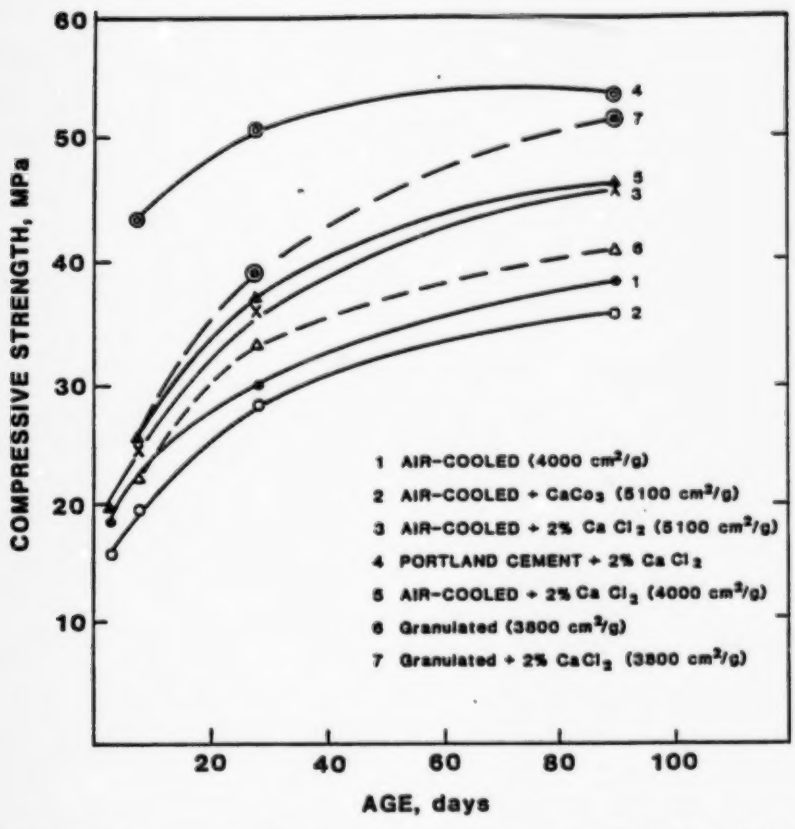


Fig. 21 — Effect of activators on compressive strength of air-cooled and granulated nickel slags ground to various finenesses (5)

JEGEL
86018

APPENDIX E

USE OF COPPER, LEAD AND LEAD-ZINC SLAGS IN BLENDED CEMENTS BY ASLAND, S.A., IN SPAIN (ESTABLISHED AT THREE PLANTS)

E1 to E4 Baragaño, J.R. and Rey, P., "Estudio De Una Puzolana No Tradicional: Escoria Cobre", Informe No. 977, Asland, Madrid, 1980. [63]
Summary in English.

E5 to E7 Baragaño, J.R., Villar Ruiz, V.M. and Sala, J.E., Utilizacion De Escorias Precedentes De La Metalurgia Del Plomo-Cinc En Cementos De Adicion, Asland, Madrid, 1986. [64]
Summary in Spanish.

ASLAND

ESTUDIO DE UNA PUZOLANA NO TRADICIONAL: ESCORIA DE COBRE

Dr. J.R. BARAGAÑO
Dr. P. REY

ASLAND

El presente trabajo aportado al 7º Congreso Internacional de Química del Cemento de París, es fruto de una investigación realizada desde 1975, respaldada por un equipo de colaboradores, tanto en el Centro de Investigación de Asland, como por los químicos e ingenieros de las plantas en que se obtienen dichos cementos.

SUMMARY

The slags obtained in copper metallurgy are vitreous, hard, compact, abrasive, of fine granulometry and are principally composed of fayalite (Fe_2SiO_4) and iron oxides in their crystallized phase.

Different assay methods show that the slags possess pozzolanic properties.

The formation of fine, deficiently crystallized S-C-H with alveolar and vermiculate structure and the possible existence of a C_4FHx type of hydrated calcium ferrite when reacted with calcium hydroxide, $Ca(OH)_2$, was shown in X-R.D., D.T.A. and S.E.M. techniques.

Cements prepared with these slags have similar characteristics to those of Portland and pozzolanic cements with advantages in workability.

The hardening curves show certain inertia in the increase in strength over short periods but with considerable later advantage, thougt the initial strengths improve well due to activation by alkaline sulphates.

Their behaviour in the presence of atmospheric agents, freezing-thawing cycles, and in alkali-silica reactions is noteworthy.

In the protection of reinforcements, when the mortars do not contain any chemical additives, the behaviour of the slag cements is similar to that of Portland super-cements (P-450) and is superior to these when $CaCl_2$ is present with normal steels, especially when 45% slags are used in their manufacture.

The durability tests with solutions of $MgSO_4$, $CaSO_4.2H_2O$, and Na_2SO_4 give results which are better than those obtained with pure Portland and pozzolanic cements. They are particularly stable to sea water.

Thus, copper slags are especially suitable for the manufacture of addition and pozzolanic cements and those which are resistant to external agents.

Experience with industrial cements and concrete manufactured with them supports this statement.

ASLAND

UTILIZACION DE ESCORIAS PROCEDENTES DE LA METALURGIA DEL PLOMO-CINC EN CEMENTOS DE ADICION

Juan R. Baragaño Coronas
Victor M. Villar Ruiz
José Esteve Sala

SEGUNDA CONFERENCIA INTERNACIONAL SOBRE EL USO DE CENIZAS VOLANTES, HUMO DE SILICE, ESCORIAS Y PUZOLANAS NATURALES EN EL HORMIGON

MADRID 21-25 Abril 1986

I. RESUMEN

Se describen las características de la escoria obtenida en la metalurgia del Plomo y del Cinc, la cual por sufrir un brusco enfriamiento a la salida del horno, se mantiene en su mayoría en forma vítrea con un tamaño regular de fina granulometría.

Como compuestos cristalizados sólo se ha detectado la presencia de FeO y ZnO en pequeñas cantidades.

El carácter puzolánico detectado en estas escorias es debido, principalmente, a la reactividad de su sílice.

Los compuestos de Plomo y Cinc retrasan la combinación entre la escoria y el $(OH)_2Ca$, aunque a edades tardías las resistencias alcanzadas son considerables y desde luego muy superiores a las logradas por un inerte.

Los cementos con porcentajes superiores al 25% de estas escorias tienen fraguados más largos que los Portland puros, aunque los mismos siempre están por debajo de los límites permitidos por los Pliegos de Recepción.

Sin embargo, esa influencia sobre los fraguados no es suficiente para regular los mismos y se necesita el aporte de yeso, en porcentajes adecuados, con los cuales el comportamiento reológicos es más favorable que otros cementos hechos con puzolanas naturales.

Las resistencias mecánicas a compresión, a primeras edades, pueden ser incluso más bajas que con una adición de un inerte, pero a partir de 7 días, el carácter puzolánico se hace patente y llega a la edad de 450 días, aún con adiciones tan elevadas como el 45%, a sobrepasar las de un P-450.

Las resistencias a flexotracción tienen una conducta aún mejor.

El comportamiento de estos cementos en la protección de las armaduras es del mismo orden a los cementos Portland puros tipo P-450 ARI

o P-350-Y, tanto en aceros normales y corrugados, e incluso con adiciones de cloruro cálcico.

En los ensayos de durabilidad, estos cementos se muestran como moderadamente resistentes a los sulfatos, y frente a soluciones de SO_4Na_2, SO_4Mg, $SO_4Ca.2H_2O$ y agua de mar, los resultados son iguales o superiores a otros cementos tipo P-450, puzolánicos o siderúrgicos tomados como comparación.

Igualmente, los ciclos de hielo-deshielo, humectación-desecación y las reacciones álcali-sílice, confirman lo apropiado de estas escorias para confeccionar cementos de adición, tanto como añadido único, o en conjunción con otro tipo de añadidos activos naturales o artificiales.

APPENDIX F

USE OF GRANULATED NICKEL SLAG IN SAND BLASTING (IMPACT FINISHING)

F1 Anon, "Inco markets slag grit", Canadian Chemical Processing. [46]

F2 to F5 Nor-Grit, Nor-Grit - Introducing the finest in abrasives for commercial and industrial blasting, Nor-Grit, Thompson. [47]

F6 to F15 Anon, "Impact finishing: synthetic abrasives erode the natural markets", Industrial Minerals, October 1977. [45]

Inco markets slag grit

Converting industrial waste to a marketable product is good business practice when it can be done. Inco has capitalized on the abrasive nature of its slag heaps at the Thompson, Man smelter to sell it as a sand blasting grit. Advantages the grit holds over silica sand are a dramatically reduced dust level when in use, and the potential to re-use the grit two or three times (sand is normally used once).

Nor-Grit Abrasives has been formed and is processing slag from a heap 65 m by 300 m, far more than enough for several years of operation. Processing is simple: two screenings to remove over- and undersized particles, then bagging. The slag is composed of silica (38%), iron (34%), alumina (5%), small amounts of magnesia, lime and sulfur, and traces of cobalt, nickel and copper.

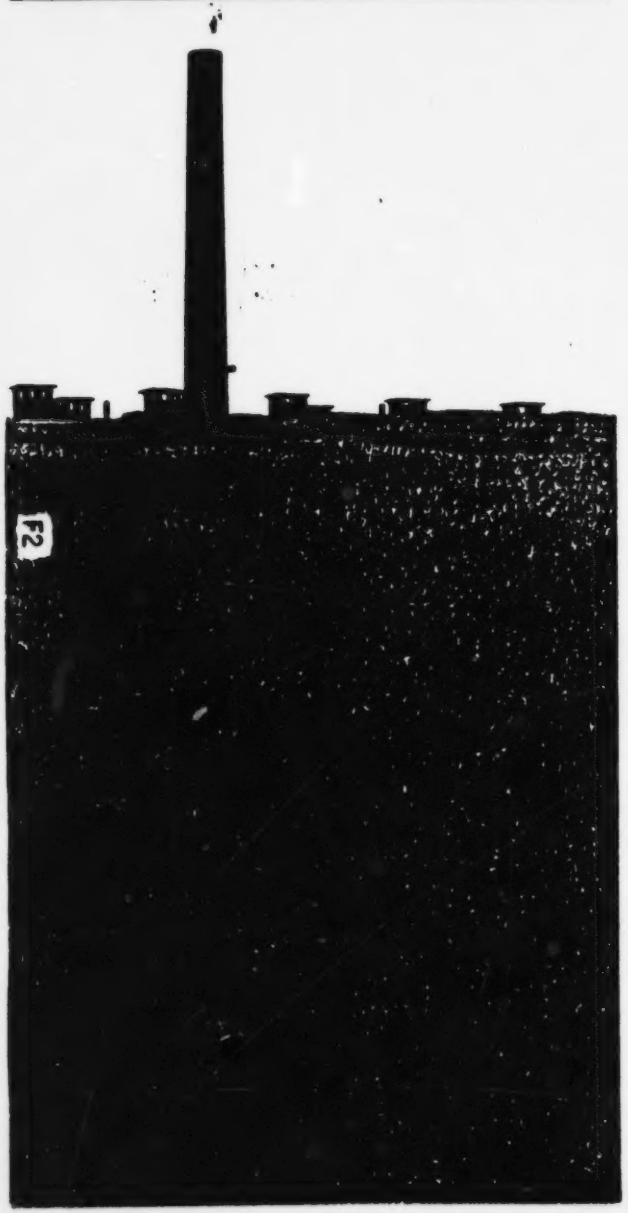
Inco has recently completed a $5-million effluent treatment plant at its Port Colborne, Ont nickel refinery. The plant has a design capacity of 7.2 million Imp gal per day to process surface runoff and refinery waste water.

The effluent is treated with lime to precipitate metals. The precipitate is then thickened, filtered and sent to the Copper Cliff smelter for metal recovery.

Inco slag finds use as sandblasting grit.

Canadian Chemical Processing

CLIP THIS FOLDER INTO YOUR THREE RING BINDER FOR FUTURE REFERENCE.



Grits available are 20-40 and 16-30.
Special grits available on request.
Nor-Grit is shipped in 25 kg bags
or in bulk as per your requirements.

NOR-GRIT

A totally Canadian owned company

NOR-GRIT

Introducing the finest in abrasives for commercial and industrial blasting.

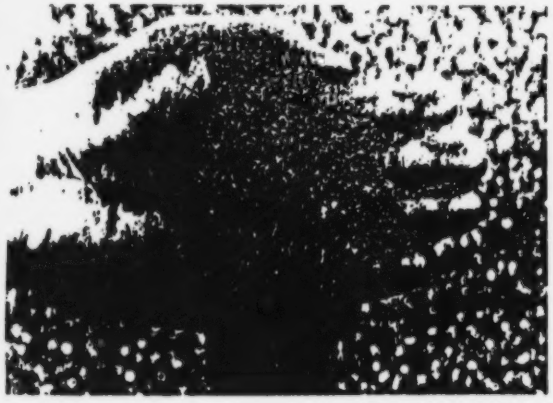
What is Nor-Grit?

Nor-Grit is a nickel slag material that does for sand blasting what sliced bread did for sandwiches. It makes life a lot easier.

Nor-Grit is tough, abrasive, clean and cheap! What more could you ask for? If you're into commercial and industrial blasting, read on. We've got a lot more to tell you.

Nor-Grit slag is comprised of 50% iron oxide, 38% silica oxide and 12% earth alkali oxides. These last are all naturally formed elements such as lime, cobalt, copper, etc. All are inert and non-toxic. The copper content is about .06% which eliminates problems of reaction and residue common to other slag materials which may have high copper content percentages.

We feel Nor-Grit is the finest abrasive available today in the sand blasting field. And we'd like you to check it out for yourself.



Raw slag material

Where does Nor-Grit come from?

Thompson, Manitoba basically. Nor-Grit is the leftover material from Inco's nickel mining operations. Taken from huge piles that would bury your subdivision, Nor-Grit is screened to its required grit size and bagged for the customer's use.

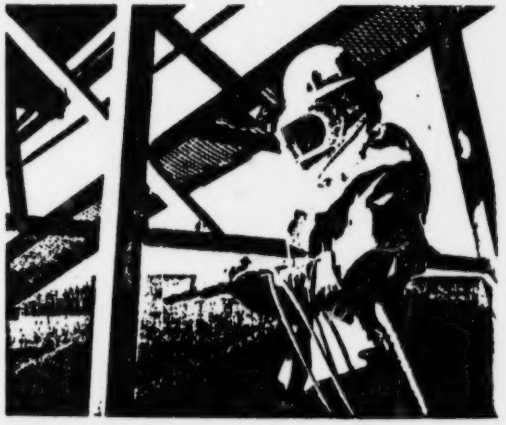
We'll ship it in 25 kg bags or in bulk — whatever you like. We usually screen 20-40 or 16-30 grits, but we'll supply any size you need. And we'll send it any way you want — train, truck or ship. As you can see, we'll do anything to keep you, the customer, happy.

Bulk loading by out-of-province carrier.

Where can we use Nor-Grit?

You can use Nor-Grit anywhere you use silica plus a lot of other jobs where you can't. It's a superior grit for removing paint, rust, scale and any other coating normally found on metal, stone, concrete and other surfaces.

If you're into mining, shipping, oil, steel, railways or similar large industries, Nor-Grit slag is for your company, but you don't have to be big to make good use of our product. Sand blasting firms, body shops, contractors, used equipment dealers and industrial painting shops are just some of the smaller operations that will benefit from using Nor-Grit. Try some. You'll never switch back to that old stuff again.



Slag blasting steel

Designed by Raven Design

Is Nor-Grit better than the competition?

You better believe it! As far as we are concerned, nothing is better than Nor-Grit slag for sand blasting. It's tough and very abrasive. You can reclaim it and use it over again. It eliminates the big dust build-up that silica gives you. There are no copper residue problems. You can remove coatings faster, clean up quicker and breathe easier.

There are no disadvantages with Nor-Grit. Only benefits! The sooner you use it, the sooner you'll get rid of a lot of headaches.

No dust with Nor-Grit (unretouched photo)

Is Nor-Grit expensive?

No way. Nor-Grit's purchase price is very competitive with silica, and it can also result in significant savings to the operator during use.

How's that, you ask? Nor-Grit can be reclaimed and reused, as it doesn't pulverize like silica. Because it's so tough and sharp, it'll cut much faster than silica and you'll use less.

Dust problems are virtually eliminated, which means that the operator can see better, work faster and has a lot less to clean up.

There's no expensive retrofitting of your sand blasting equipment. Just use Nor-Grit like you used silica. It's that easy!

Bags being pallet loaded for shipment.

[illegible] hazards with Nor-Grit?

Dust, which has now become synonymous with sandblasting, is now reduced by approximately 90% with Nor-Grit slag. With proper sandblasting gear there are absolutely no health or safety hazards to the operator!

As a matter of fact, slag material for sand blasting has been approved by the Department of the Environment in the Province of Saskatchewan.

Operators no longer have to work in a cloud of silica. They can now actually see what they are doing. They can work faster, easier and cleaner.

There's no fighting progress and Nor-Grit slag means progress in the commercial and industrial blasting industry. At the rate we're growing you might soon forget about "sand" blasting and only talk about "slag" blasting.

Obscured vision when sandblasting with silica sand (unretouched photo).

F4

Printed in Canada

YES,

- ◯ I would like a free sample kit.
- ◯ I would like a free 25 kg. sample bag.
- ◯ I would like prices for Nor-Grit.

Name _____

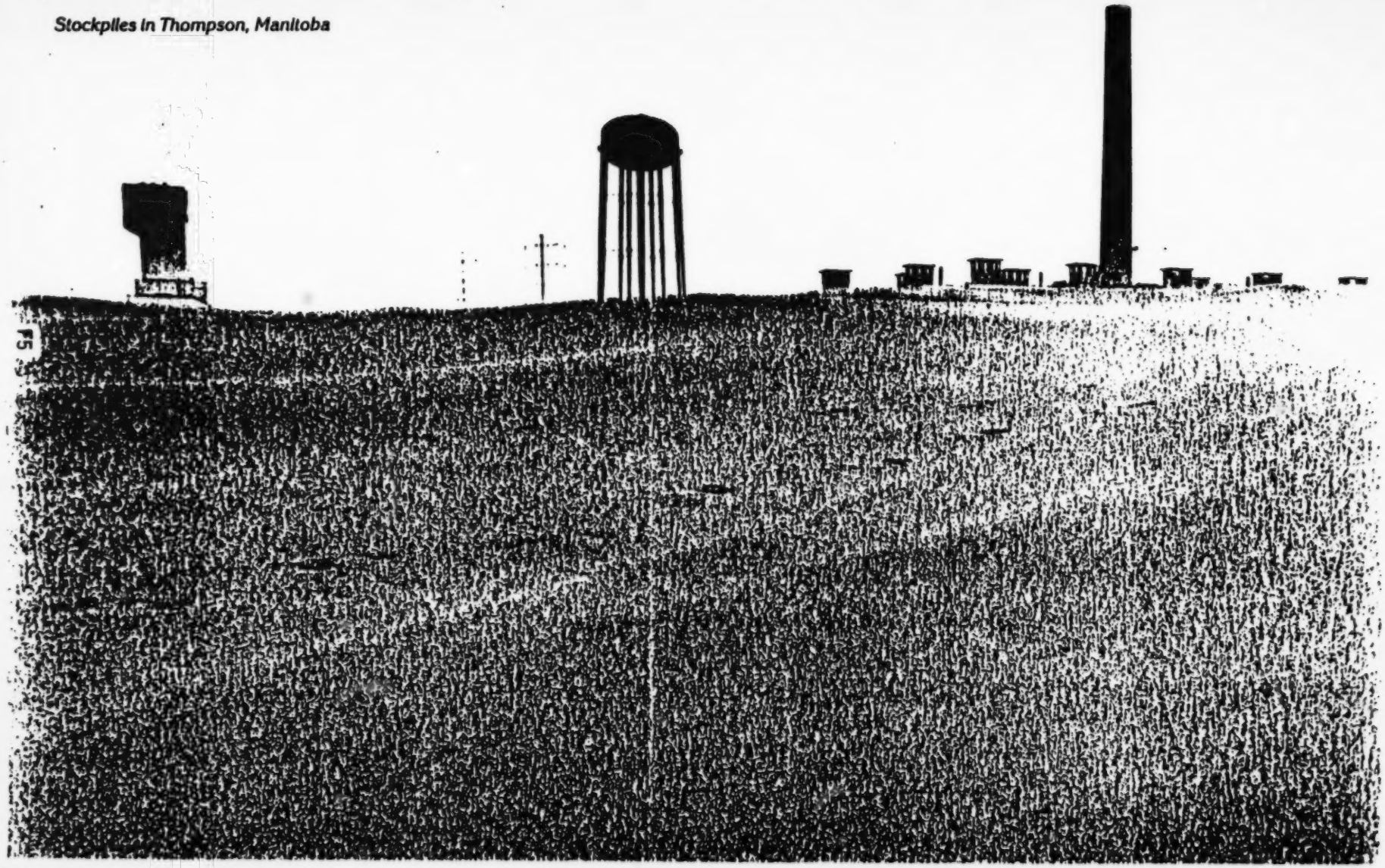
Company _____

Address _____

City _____

Postal

Cut out and mail coupon to:



Stockpiles in Thompson, Manitoba

Impact finishing: synthetic abrasives erode the natural markets

Legislation in many countries, particularly in Europe, has outlawed the use of materials containing free silica—largely silica sand—as an abrasive in impact finishing (formerly sand blasting). The increased popularity of impact finishing in many industries fostered the search for an effective and cheap alternative to silica sand. The following article looks at the state of the art and the the abrasives now competing to fill the gap.

Grotesque rock forms, desert pavements, and rock faces polished to a mirror shine by driving desert sands have been admired for centuries. More recently, the frosting effect of the sand on the window glass formed the basis for this phenomenon to be harnessed as an industrial tool. Thus the sand-blast machine was designed, manufactured, and patented by B. C. Tilghman of Philadelphia in 1870 in the UK. Initially its use was restricted to cutting stone and grinding and ornamenting glass, but then it was used to clean and finish new files. Subsequently it began to replace the traditional pickling method of cleaning and descaling steel and iron parts prior to enamelling, galvanising, painting, etc.

The industry expanded through the early parts of the present century so that today it is a highly complex and sophisticated business. These developments have been paralleled by an increase in nomenclature. When abrasives other than silica sand began to be used 'sandblasting' became a misnomer and terms such as 'gritblasting' and 'shotblasting' had to be coined to describe the use of angular grit and rounded shot as the abrasive. Impact cleaning was then used as an umbrella term for these activities as well as things such as 'shot peening' and 'vapour-blasting', but this incorrectly implies a solely cleaning activity. Thus probably the best and most comprehensive term is 'impact finishing' since it encompasses all abrasive and all blasting activities.

Modern applications and equipment

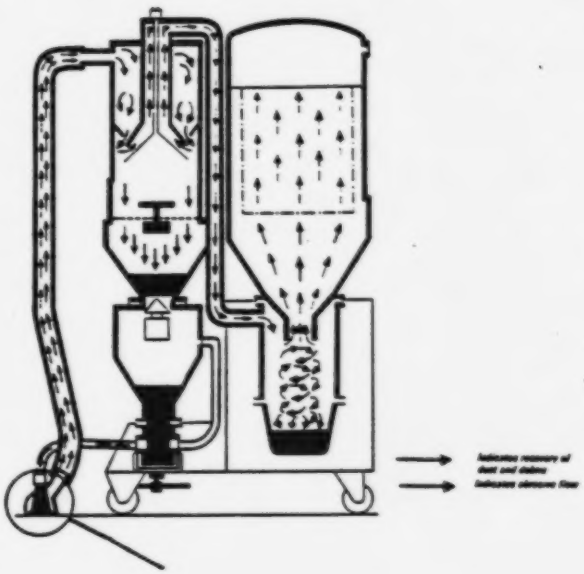
Impact finishing is used today for a range of applications including the removal of paint, rust, and burrs, rendering a material rough or smooth, and strengthening or shaping an object. The scale of the job ranges from cleaning a bridge to smoothing the point of a hypodermic syringe.

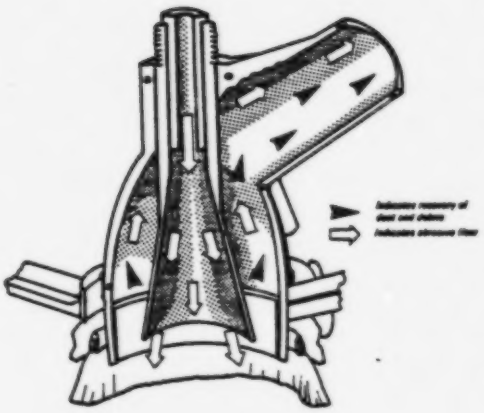
Permanent structures such as buildings or bridges obviously require portable impact finishing equipment. In most cases the machine is made up of a pipe and nozzle, much the same as a garden hose although obviously manufactured from considerably more resistant materials, through which an abrasive is forced by compressed air or water. Because the abrasive is unlikely to be recovered from such an open system, a relatively cheap material such as silica sand or metallurgical slag is used. The severe limitation on the type of abrasive that may be used, together with the dangers of contamination and interference with neighbouring machines or work, is obvious.

This problem prompted the development of the famous

'Star Wars' comes to Britain. A very space-age uniform protects the worker whilst cleaning up the Tower of London with a high pressure abrasive gun. *(Photo: London Stone Ltd.)*

The Vacu-Blast Closed Circuit Gun

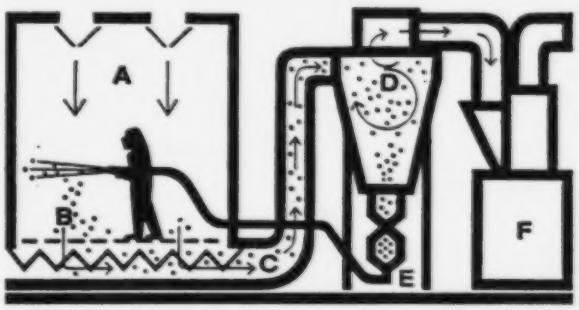




'Vacu-Blast' system in the UK in 1950. Essentially the system is composed of a gun with two concentric tubes — the inner one delivering the abrasive to the surface whilst the anulus sucks away the mixture of abrasive and the debris. A circular, flexible bristle brush is fixed to the outside rim of the gun to prevent the abrasive from escaping whilst at the same time allowing air to enter the system. Being flexible the gun can be used for intricate and uneven surfaces. The overall system is com-

recycling the abrasive and filtering out the dust debris. The 'Vacu-Blast' system may also be used as an open circuit merely by turning off the suction mechanism. The system has increased in size, particularly for use in the ship repair yards, and the recycling mechanism can handle material down to 10 microns.

Complex articles of a more manageable size — perhaps up to a railway engine — are often blasted in a specially constructed blasting chamber. This was merely a room constructed specifically to blast objects in enclosed surroundings which in turn would allow the abrasive to be recycled in safety. A major breakthrough in the technology came about with the introduction of the pitless blast chamber shown in the diagram below. The chamber can be moved around relatively easily



A. Blast Room
B. Mini-hopper floor
C. Blast media recovery duct
D. Cyclone reclaimer
E. Pressure vessel
F. Dust collector

and the continual removal of abrasive and debris by a constant downdraught of air clears the atmosphere for the work. Standard chambers as big as 130 feet by 30 feet can now be purchased, and larger versions can be custom built.

In addition to the 'Vacu-Blast' system which is based on compressed air, there are a number of other methods of firing the abrasive. Tilghman Wheelabrator Ltd. produce an airless mechanical blast system called the **Wheelabrator,** and there are several other versions of the centrifugal blaster. The machine has a motor driven centrifugal wheel designed to hurl abrasive in a controlled stream at about 270 feet per second. The system is a closed one—the abrasive is gravity fed into a rotating impeller, through a series of openings, and so to the rotating blades which have a capacity to handle up to 480 lbs. of abrasive per minute. The abrasive and debris falls into a hopper with a screw conveyor and it is put through an air-wash separator to remove debris and broken down abrasive. The centrifugal blaster has the advantage of not needing a supply of compressed air, but it covers a wide area and is most useful for flat uncomplicated work faces.

Hydroblasting is another process used quite extensively. Water is used rather than air which gives a scouring action, and there is little or no problem from dust due to the moisture. A further variety is **vapour-blasting** which uses steam rather than water.

A wider spread of applications

The traditional use of blasting to remove scale and paint from bridges, ships, and railway carriages, the sand from moulds, and the industrial grime from buildings is still very active. Although the more recent additions to the

A subject close to our hearts. The effect of cleaning up type using impact finishing.

range are small in comparison, they are nevertheless extremely important. These esoteric uses include the cleaning of suede, deburring computer components, finishing turbine blades, and finishing the surface of high quality porcelain.

One other increasingly important species of blasting is **shot peening.** This is the cold working of the surface of a metal by the impact of spherical particles such as steel, iron, or stainless steel shot, glass or ceramic beads, or any other hard spherical object. Under impact a thin surface layer of the work face undergoes plastic deformation thus altering the topography, hardening the surface, and setting up a state of residual strain. The overall effect is to improve the fatigue strength by up to 50%. This is particularly useful for strengthening vital engineering parts such as gears, bearing surfaces with sectional changes, helicopter prop drives and blades, and the like.

Another important application of peening is to improve the strength around the heat-affected zone of welds. When the welded area cools it contracts and sets up internal stresses in the metal which is itself brittle due to the metallurgical changes. Although obviously not the prime objective, shot peening an automobile also reduces its overall weight by around 130 kilogrammes. **Peen forming** is rapidly gaining acceptance as a means of manufacturing aerodynamically perfect shapes. The system is based on the fact that when one side of a metal sheet is peened it develops a spherical shape, convex on the peened side, which can be made to exact measurements. However, great care has to be taken to adjust for the changes in the linear dimensions of the product.

Powder coating—that is where materials are treated with powders, for example epoxy and nylon resins, to give a specialised set of properties — is a growing field in modern industry. Impact finishing is now used extensively to clean and prepare the surface prior to powder application, particularly by electrostatic methods.

Another blasting procedure goes by the splendidly descriptive title of **plastic deflashing.** The object is to remove the flash or excess plastic from moulded products which was previously removed by cutting or hand trimming. A 'gentle' abrasive has to be used, for example plastic pearls or ground walnut shells.

Factors affecting the finish

The finish of any material undergoing blasting depends upon a number of variables which have to be controlled accurately, particularly for shot peening or artistic work. One of the main factors is the air or water pressure of the jet since this regulates the speed of impact of the abrasive. This can be altered by adjustment to the output compressor, although developments in nozzle design have had a bearing on the situation. In the early 1950s the traditional parallel bore nozzle was replaced by the supersonic variety. The new nozzle, lined with tungsten carbide or boron carbide to give an operating life of 1,000 hours plus, eliminated the shock wave effect and so allowed the abrasive to move through the throat of the nozzle faster than the speed of sound. Another innovation of the 1950s was the commercial development of dry honing. The fine abrasive feed is delivered through an aerated valve which eliminates the need for the exceptionally fine media to be delivered in a water slurry.

Allied to the air/water pressure and the design of the nozzle is the distance between the work face and nozzle and the angle of contact. Both these factors dictate the area over which the abrasive impact is spread, that is the density of abrasive per unit volume of work face. However, one of the most important factors is the size, shape, and hardness of the abrasive used. The choice has widened considerably over the past few years.

The abrasive choice

Although progress has been made from the sandblasting of the 1870s to the impact finishing of the 1970s, the open system still remains for the most part dirty and dusty. With the recognition of the effects of silicosis,

Contact the Specialist for . . .

DIATOMITE
CLAYS and MINERALS
Bentonites—Filter Aids

LIGNOSULPHONATES
Calcium & Ammonium Based

NORWEGIAN OLIVINE
(Ex. A/S Olivin, Aaheim)

PRODUCTION CHEMICALS LIMITED

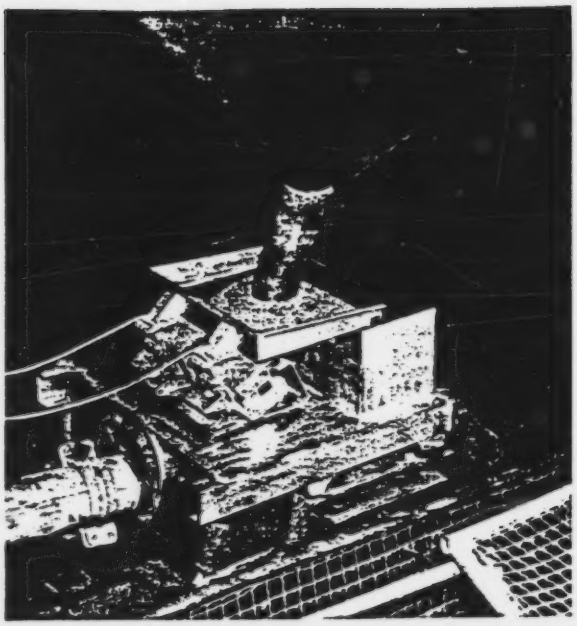
Speakers House, 39 Deansgate,
Manchester M3 2AT.
Telephone: 061-834 3396/7 and 6302.
Cables: Chemprodux, Manchester.
Telex: 667330.

both in medical and industrial circles, tighter restrictions on the type of abrasives that could be used in impact blasting were implemented. However, the law regarding the use of various materials is still far from uniform. The use of free silica abrasives (i.e., silica sand) has been banned in the UK and most other Western European countries, although in the USA—usually a prime mover if there is any banning to be done — still allows its use. In fact the use of metallurgical slags, largely the replacement of silica sand in the UK, is not used in the USA since the risk of metallic poisoning is regarded as too high. Nevertheless, the writing is on the wall for abrasives containing free silica, and this is giving increased impetus to the development of cheap and effective alternatives.

The main factors in the choice of the abrasive are the surface required, the cleaning speed, and the maintenance of the plant. This in turn is related to the cost of the abrasive, its performance, and the type of plant. The object is to reach a balance since there is no abrasive which at the same time cleans the fastest, lasts the longest, and produces the least wear on the plant. The best performance is achieved by using the smallest pellet size that can break or loosen the surface contaminants, since the finer the particles the greater the number of impacts per kilogramme of abrasive, and therefore the greater the coverage of the work face. The quality of the abrasive also has to be maintained — mainly by avoiding irregular shapes (in the case of shot), correct grading, freedom from voids and hollows, density, absence of residual elements and the hardness.

Metallic abrasives

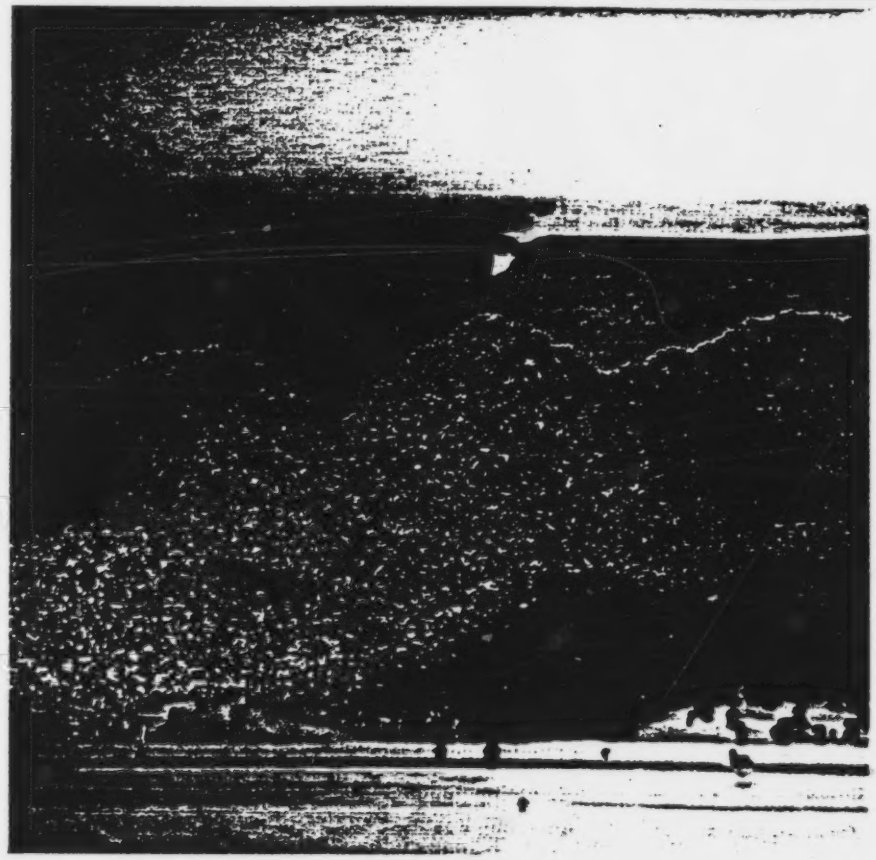
Metallic abrasives now account for the bulk of the abrasives used in impact finishing. Chilled iron shot and grit has become very popular as the bulk abrasive in impact finishing. The product, which has a typical chemical analysis as shown below, and no free silica, consists of hard, sharp, angular pellets with an excellent cutting action. During the production process—in the case of shot this consists of pouring molten iron through a jet of steam or water—great care has to be taken to maintain the quality and composition of the material. Because the chilled iron is extremely hard, it is used where the maximum cutting is required, and even though it breaks down rapidly its efficiency is maintained due to the constant creation of new edges. Special types of iron grit are available—high duty or



A bank of Eriez 20A Dual Feeders at Barton Abrasive Ltd.'s Middlesbrough plant in the UK. The electro mechanical vibratory feeders control the flow of shot which is converted to grit by crushing.

Some abrasives commonly used in impact finishing

Abrasive	*Chemical formulae*	*Hardness* — *Mohs*	*Hardness* — *Knoop*	*Particle shape*	*Fracture*	*Remarks*
Steel shot/wire/grit	Steel with 0.6–1.25% C; 0.2–1.1% SiO_2; 1.25% max Mn; 0.08% S; 0.08% P	7–8	780–1,190	Round/ angular	Angular	The major impact finishing abrasive now used. Takes approx. 75% of the market
Chilled iron shot/ grit	Iron with 2.85% C; 1.35% SiO_2; 0.3% Mn; 0.14% S; 0.004% P.	8.5	1,190–2,200	Round/ angular	Angular	
Silica/sand/quartz/ flint	SiO_2	7	788	Round/ angular	Angular	The original abrasive. Largely replaced due to silicosis risks. Banned in many countries
Fused alumina	Al_2O_3	9	1,950–2,200	Angular	Conchoidal	Gaining universal acceptance as replacement for silica sand.
Natural corundum-emery	Al_2O_3	9	1,950–2,200	Angular	Conchoidal	Natural product mined mainly in Greece & Turkey. Retains popularity.
Silicon carbide	SiC	9	over 2,000	Angular	Uneven	Usually too expensive to be used in impact finishing.
Metallic slag						
Cu	32–45% SiO_2; 25–33% CaO + MgO; 24–35% FeO					increasing in importance except for North America.
Pb	28–37% SiO_2; 16–21% CaO + MgO; 30–45% FeO	6–7	560–820	Angular	Angular	
Olivine	$(MgFe)_2SiO_4$	6–7	560–820	Angular	Conchoidal	Market largely European—esp. Scandinavia & Italy.
Garnet	$Fe_3Al_2(SiO_4)_3$	7.5–8	788–1,190	Angular	Uneven	Production in New York state to east coast, Idaho to west coast of USA. Large output from Australia coming on stream.
Staurolite	MgFeAl silicate	7–7.5	788–900	Rounded	Conchoidal	Produced in Florida, USA, as by-product of mineral sands. Local market.
Glass beads	soda-lime glass	5–5.5	483–550	Spherical	Angular	Increasingly popular, especially for peening.



VASILGRIT

expendable abrasive from Holland

IN BULK OR BAGS

from 20 tonnes to 2,000 tonnes per consignment

VASILGRIT—HARD, TOUGH, SHARP
CLEAN, SILICA-FREE
CHEAP

contact:

VAN LOON VREESWIJK BV

PO Box 1013, Nieuwegein
Netherlands

Tel: 3402-32434 Telex: 47533

Hardness Scales

MOHS scale	*Material*	*Knoop scale*
1	Talc	12.3
2	Gypsum	61
3	Calcite	141
4	Fluorite	181
5	Apatite	483
6	Feldspar-orthoclase	621
7	Quartz	788
8	Topaz	1,190
9	Corundum (Al_2O_3)	2,200
10	Diamond	8,200

heat treated material — which are useful for certain fields. Although chilled iron has a very low initial cost, its application is restricted since it has the shortest working life and the highest maintenance costs.

Steel grit and shot is much softer than chilled iron and thus has the advantage of increased resistance to breakdown. In turn this is reflected in a reduction in machine wear. It also has the advantage of excellent peening characteristics giving the working surface a smooth dull finish. It is manufactured by melting down selected low sulphur and phosphorus steel scrap in an electric arc furnace and atomising it into random sizes. The product is then heat treated (tempered and hardened) and quenched to give a specific structure prior to screening. An ideal mixture of steel shot for impact finishing contains most sizes — the large shots breaking down the large particles and the smaller ones operating as a cleaning medium. Stainless steel shot and wire is also used for special purposes. Steel shot is rapidly becoming the most popular of all the abrasives used in impact finishing.

Synthetic abrasives

A large number of blasting abrasives are now made synthetically. This trend is a general one in the abrasives industry, either because high quality natural products are no longer available in large quantities or because they cannot consistently come up to the increasingly stringent specifications. The most successful synthetic abrasive is **fused alumina**, Al_2O_3, the synthetic form of natural corundum. Since its development by Charles B. Jacobs in 1900, aluminium oxide has become widely accepted as a bonded, coated, and loose grain abrasive, as well as a refractory. It is manufactured by fusing bauxite with ground coke and iron borings in an electric arc furnace at around 2,000°C. The molten alumina is allowed to cool at a rate depending upon the crystal size required. This is then crushed and sized. Among the manufacturers in the UK are *Carborundum, Universal Abrasives*, and *Norton Abrasives*.

Aluminium oxide has a hardness of 9 on the Mohs scale of hardness (equivalent to 2100 on the Knoop scale) and is one of the most stable ceramic materials known. It has a melting temperature of over 2,000°C,

Typical Chemical analysis [%]

Aluminium oxide*

	White	*Brown*
Al_2O_3	99.53	97.03
SiO_2	0.10	0.5
Fe_2O_3	0.10	0.2
Na_2O	0.33	0.02

Silicon carbide†

	Green	*Black*
SiC	99.45	98.73
SiO_2	0.20	0.48
Fe_2O_3	0.05	0.09
Al_2O_3	0.05	0.10

Garnet**

SiO_2	36	Al_2O_3	15
Fe_2O_3	34	MgO	3
MnO	11	CaO	1

**The Carborundum Co. Ltd.,* †*Universal Abrasives;* ***Idaho Garnet Abrasive Co.*

from most strong acids, chemicals, or metals other than the alkali metals. Fused alumina usually comes in two main grades—lower quality brown and the higher quality white (see accompanying tables).

Being a sharp angular grit, aluminium oxide gives a matt finish to most metals and can be used economically in a closed system environment such as Vacu-Blast. Its range of application is almost limitless — the removal of sand from castings, surface preparation prior to enamelling, electroplating, painting, or bonding, etching, descaling, deburring, burnishing, or polishing.

Although **silicon carbide** is used extensively as a loose abrasive, its use in impact finishing is limited. This is largely due to the fact that it is relatively expensive and the angular grain shape is too destructive for most purposes. Its advantages over say aluminium oxide do not warrant the extra cost.

Natural aluminium oxide survives

Despite the tremendous rise in the popularity of synthetic aluminium oxide, its natural equivalent has survived. For example, *Bendix Abrasive* (American Abrasive Corp. up to 1969) of the USA markets microcrystalline **corundum** under the trade name "Herculon". The company claims that the structure of the natural product resists shattering and thus gives a working life up to 50% longer than the synthetic material. The long cooling time of the natural product forms a crystal averaging 25 microns rather than the 500 micron size in synthetic fusing.

Southern Rhodesia was the major source of corundum until sanctions cut off the supply in 1968. The major source is now South Africa. The demand for corundum in the future, both as a blasting and a general purpose

floatex separations ltd. ENGLAND

Leading manufacturers of sand washing, classifying and processing equipment for the glass and industrial minerals industries.
Our products include:
Upward Current Classifiers
Attrition Scrubbers
Conditioners
Froth Flotation Cells
Cyclones
Thickeners

Buswell's House, Crick,
Northampton.
Tel. 44 (788) 822387 Telex 21792

Typical chemical composition of some commercial slags.

	WOLVERHAMPTON ABRASIVES J. Blast 1	WOLVERHAMPTON ABRASIVES J. Blast 2	APPLEBY ABRASIVES Capper Pass	APPLEBY ABRASIVES Staveley	VASIL-GRIT	MELCHEMIE Auker	MELCHEMIE Aran	SCANGRIT Grit	SCANGRIT Dust	NATURAL GARNET
FeO	45.0	32.1		38.00	11.4			44.0	41.55	40.0
Fe_2O_3		1.3	39.3	1.35	1.7	15.0	36.0	0.6	3.15	
SiO_2	22.0	25.3	21.1	26.0	43.2	40.0	30.0	37.6	38.4	40.0
Al_2O_3	8.0	9.4	8.2	9.2	28.1	30.0	7.0	4.0	3.35	
CaO	2.0	6.2	12.9	8.5	5.3	7.0	13.0	6.0	5.86	20.0
MgO		2.1		3.2	2.3	3.0		1.9	2.15	
TiO_2		0.51		0.6	0.54	1.0		0.42	0.03	
MnO		1.3		0.9	0.4			0.4	0.27	
ZnO	8.0	11.7	11.9	4.5	0.13		6.0	0.65	1.68	
SnO_2 (Sn)	(0.5)		0.3							
CuO (Cu)	(1.5)	1.6	0.16	1.1	0.1			0.41	0.47	
PbO (Pb)	(0.5)		(0.3)				TRACE		0.04	
SLAG TYPE	*COPPER*		*TIN*	*IRON*	*BOILER*	*IRON*	*COPPER*	*COPPER*		

Source: Scangrit

abrasive, clearly will depend upon the supply position. It will supply local markets but synthetics may be more widespread. One factor that may be in corundum's favour is the very recent trend back to natural abrasives in view of the higher energy costs of production.

With this in mind, another natural form of aluminium oxide, although also containing magnetite, titania, silica and magnesia, is emery. Some emery is being mined in the USA, but the main supply originates in Turkey and Greece. The bulk of Turkey's 100,000 tpa output is exported to the USA, the Netherlands, the UK, and France. The Greek production is concentrated on the island of Naxos in the Aegean Sea. Its major end use is now in the manufacture of non-skid floors and coated abrasives, although some is employed in blasting.

Slag as an abrasive

The smelting of lead, zinc, tin, iron, etc., produces a granulated black slag which is now regarded as waste. The tonnages involved are extremely high, for example, between half and three tons of slag is formed for each ton of zinc smelted. The composition of the slag varies from ore to ore and from smelter to smelter, but it is usually around 20-50% iron, 15-30% silica, 18-25% lime, 1-6% alumina as well as variable, although hopefully low, amounts of lead, zinc, etc. Most slags used to be a composition of dicalcium silicate, but newer processes produce a product nearer to wurtite, that is approximately olivine. In most cases the slag is a problem material, usually dumped or used as road fill or as clinker in the manufacture of cement. However, probably the fastest growing use is as a blasting media.

Metallurgical slag has a number of attributes which makes it ideal as a replacement for silica sand as the main abrasive used in blasting. It is a vitreous glass which is dense and hard, it is relatively cheap, and most importantly most are completely silica free. As in the manufacture of glass itself, the silica sand is converted to combined silicates which are harmless even when inhaled as a dust. However, as outlined above, there are slags and slags, some of which are much more suitable for this purpose than others. Firstly, it must contain the minimum amount of metal contaminates such as lead or copper since this is a hazard both in the processing and in the use of slag abrasives. It is advantageous to use a slag with a high iron and alumina content since these ingredients increase the hardness factor, whereas the inclusion of alkalis such as lime or magnesium tends to have the opposite effect.

In the UK the processing of metallurgical slag is becoming a large business. *Appleby Abrasives* process iron slag supplied by its associate British Steel; *Wolverhampton Abrasives* process material from Imperial Metal Industries; and *Scangrit* of South Humberside produce an abrasive based on imported copper slag. One of the big consumers in the UK is the North Sea oil industry. It is estimated that between 250,000 and 300,000 tpa of processed slag abrasive is used on the oil rigs. Ironically, most Arab countries have banned the use of sand for blasting purposes and there is obviously a potential market for slag.

In continental Europe the use of slag in blasting is

MINERAL ABRASIVES • CEMENT RAW MATERIALS

"GRAN-BLAST-GRIT"
LARYMNA, GREECE
"SAF-T-BLAST"
TAMPA, FLORIDA

BAUXITE
GYPSUM
IRON ORES
SLAGS

WORLDWIDE MATERIALS & SHIPPING CO. LTD.

Offices:
5 Green Street, Flat One,
London W1Y 3RG, U.K.
Tel: (01) 493 1758.
Telex: 28857 PEDSEN G.

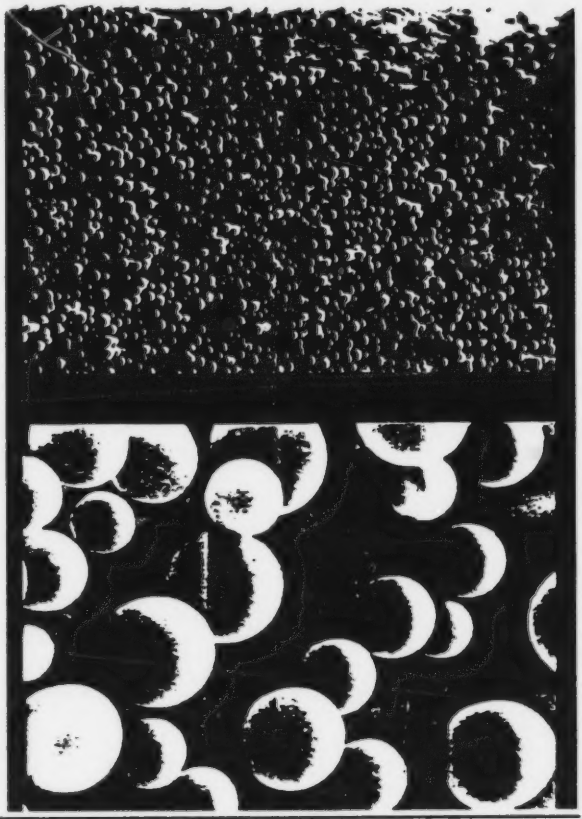
4328 East Tradewinds Avenue,
Lauderdale-by-the-Sea,
Florida 33308, U.S.A.
Tel: (305) 776-4482.
Telex: 514-527 NSS FLORIDA.

increasing. In the Netherlands for example, the Sand Blasting Order of 1957 banned silica sand as a blasting media. One of the various materials designed as a replacement is 'Vasilgrit', a copper slag produced by *Van Loon Vreeswijk* of Nieuwegein. The use of slag depends upon availability—already material is entering international trade since some slags are much more suitable than others.

Other parts of the world have a different point of view regarding the advantages of slag utilisation. Despite the New South Wales Department of Labour in Australia and the Industrial Hygiene Foundation of America recognising that granulated slag contains no free silica, its use is still in its infancy in these countries. The reasons behind this stand, or why silica sand — which has been outlawed for these uses since 1949 in the UK — is still allowed in the USA is uncertain. In any event it will be interesting to see the events over the next year or so.

Glass beads

It may come as a surprise to some people that glass, in the form of a sphere or bead, is safe to use in blasting. In fact the use of glassbeads is probably one of the largest growth areas in the impact finishing field. Their major advantages include ease of dispersion, non-caking and free flowing charactristics, and chemical inertness. The beads are usually manufactured from high grade crown glass, high in silica and low in lead, and are annealed in the spherical shape to equalise stresses. This in turn reduces the possibility of wear and fracture. Most manufacturers guarantee 85% true spheres



EASTFIELD ROAD, SOUTH KILLINGHOLME, GRIMSBY, SOUTH HUMBERSIDE, DN40 3NF U.K.

Telephone 0469 74715/7. Telex 527047

SCANGRIT

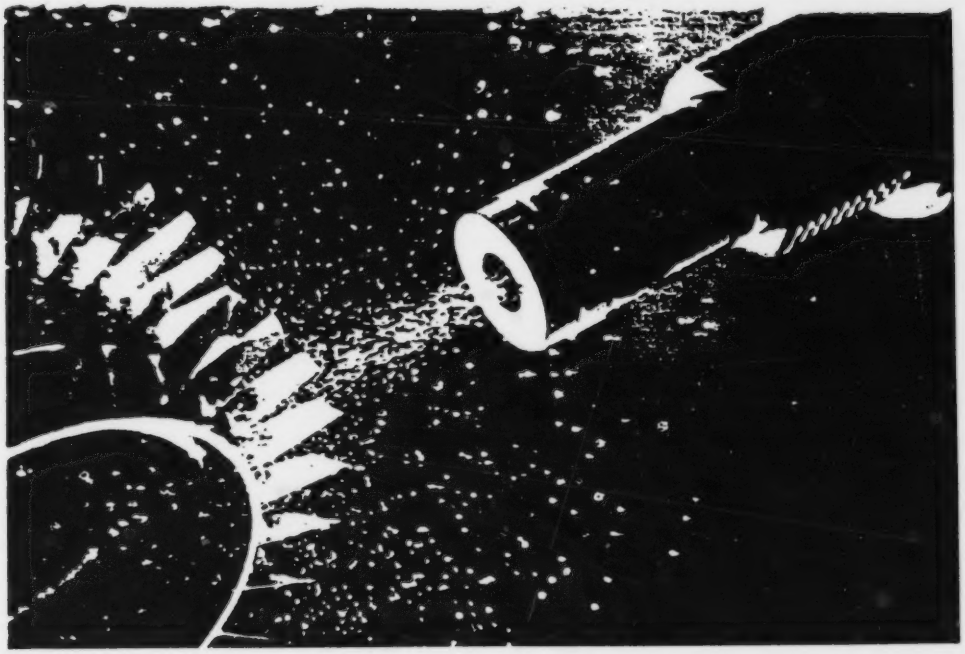
EXPENDABLE ABRASIVE FOR GRITBLASTING

STANDARD GRADES

ABSOLUTELY SILICA (and quartz) FREE, unique refining process ensures negligible amounts of noxious metals.

Delivery ex-stock UK and Europe

H&SE Approved Admiralty approved List



The moment of impact as glass beads shot finish a set of turbine blades. Glass beads are now in widespread use to increase the fatigue life of critical components.

and never more than 1% with angular or sharp edges.

Glass beads have a number of advantages over steel or iron shot or angular abrasives. The glass is inert and therefore can be used on most materials without fear of contamination. In addition, being a spherical shape, the chance of being entrapped in the work surface is reduced considerably. In addition, there is little chance of dusting, no change in the chemical or electrical characteristics of the surface, the surface can have a bright, matt, or fine finish, and the consistent quality and shape of the beads result in a very consistent end product.

One important point is the question of health risks. It is generally understood that the use of glass beads does not in fact cause silicosis since the sand in the glass batch is completely converted to combined silicates during production. Quoting from 'Industrial Toxicology' by Fairhall, "It is important to distinguish between free silica and combined silica. Free silica refers to sand, flint, agate, and diatomaceous earth. Silica in the free state (not free silica) are silicates and are considered innocuous when inhaled as dust except for talc, mica, fibrous silicates (asbestos)." This argument can be applied to a number of other abrasives including metallurgical slag.

The potential use of glass beads in the impact finishing industry is extremely wide, particularly in precision cleaning, finishing, or peening. There are a number of manufacturers in the world, for example *Potters Industry Inc.* of New Jersey (with subsidiaries throughout the world), the *Cataphote Division of Ferro Corp.* of Jackson, Mississippi, and *Vacu-Beads*, a division of Vacu-Blast Ltd. of the UK.

Some natural alternatives

Although the synthetics seem to have stolen the limelight recently in the impact finishing field, there are still a number of natural alternatives that may be used. Obviously, natural mineral deposits are only found where they are whereas factories and plants may be sited near the market. However, if a supply of natural minerals is within the market area then there is a possibility that the synthetics — which are usually merely a copy of nature — will suffer. The recent trend back to natural abrasives due to the vastly increased energy costs may spur their renewed use.

SPANISH DUNITE

STEPHAN PASEK ET CIE S.A.

Chaussée de Dinant, 13

5198 - ANHEE - BELGIUM

Telex: 59144.

Telephones: 82/61.17.73 - 61.19.81 - 61.19.82

Production capacity:

600.000 M.T. a year.

Qualities available:

0-3mm., 0-5mm., 10-40mm.

Olivine

Olivine is an important mineral that is well suited to impact finishing. It has a hardness of 6-7 on the Mohs scale of hardness and contains no free silica. At the moment the major areas where it is used as a blasting abrasive are the major producing areas — particularly Scandinavia and Italy. Silica sand has been banned in Sweden since July 1976 and therefore a number of alternatives have been tested such as copper slag, slag from coke-fired power plants, and olivine. The other alternatives like aluminium oxide, garnet, steel shot, etc., are less popular, although the gradual introduction of the recyclical abrasive machine of the Vacu-Blast type is making them more so. A similar situation may be expected to occur in Norway since silica sand is about to be legislated out of use in the very near future.

Beach sand alternatives

A number of members of the beach sand group have been tried as an abrasive in impact finishing. Although zircon would be ideal, it is relatively expensive. One successful alternative is staurolite, a 45% Al_2O_3 product with a Mohs hardness of around 7. In the USA for example, *E. I. du Pont de Nemours and Co. Inc.* market a product containing 77% staurolite, 10% tourmaline, 4% titanium minerals, 2% kyanite, and 3% zircon, which is extracted from the company's beach sand deposit at Starke, Florida. The product is scrubbed and chemically washed to give a clean, uniformly sized, round product in three grades—coarse (US standard seive no. 55), 'Biasill' (90 mesh) and 'Starblast' (80 mesh).

Garnet

Garnet production and consumption to date has been dominated by the USA. In recent years the US has produced around 22,000 tpa out of a world total of less than 27,000 tons. The major producers are in New York State — *Barton Mines Corp.* and *Interpace Corp* — and in Idaho — *Idaho Garnet Abrasive Co.* and *Emerald Creek Garnet Milling Co. Inc.* The market for the west and east coast of the USA is obviously divided between the two major producing areas. Another important source of garnet has recently come on stream — a large alluvial deposit near Geraldton in Western Australia operated by *Target Minerals*. Initial output is expected to be around 12,000 tpa, mostly in 50 kilogramme bags. The mineral composition is 95% garnet (almandine), 3% ilmenite, 1% quartz and 0.25% zircon. Other garnet production also includes small quantities from Sri Lanka, Argentina, Malagasy Republic, South Africa, and Tanzania.

The producers of garnet claim a number of advantages of the natural material over other abrasives. Garnet has a fast cutting action, it requires around 60% of the air pressure necessary for silica sand, does not contaminate the work surface, and breaks down slowly thus increasing its life. Of course in common with all the silica sand alternatives, garnet has no free silica and its high alumina and iron content makes it extremely hard.

Silica sand

For some time now, silica sand has been the villain of the piece as far as impact finishing is concerned. It has been banned in most European countries for a number of years, and in the UK it was outlawed back in 1949. The only large market where it still survives is the USA. The emotive reaction of the public to pneumoconiosis and silicosis in mines has certainly killed silica as a blasting media. Although flint contains free silica, various producers are pushing its excellent cutting properties, its resistance to wear, and its complete inertness. However, it can only be used where dust emission is strictly controlled.

POSSEHL ERZKONTOR GmbH

2400 LÜBECK

P.O. Box 1623
Tel.: 0451-71171
Telex: 26426

Branches: DUSSELDORF—HAMBURG—NEW YORK

ASBESTOS
BAUXITE
CHROME ORE
MAGNESITE
FLINTCLAY
KYANITE

GARNET

FLUORSPAR
SUZORITE MICA
IRON ORE
MANGANESE ORE
ZIRCON SAND

Vegetable and others

A great variety of other products have been used from time to time for blasting. It would probably be easier to name the materials that have not been used, but examples of abrasives include crushed almond, coconut, and walnut shells, corn cobs, rice hulls, and oat husks. These are largely used for delicate jobs like deflashing plastics. Nylon shot is also used for this purpose and polystyrene shot is often used for peening aluminium or magnesium alloys. Even sugar and salt have been used for certain jobs although obviously not if there is any water about.

Outlook

To the uninitiated the field of impact finishing is larger and more complex than imagined, and its impact on everyday life is striking. Specific consumption figures are difficult to obtain and future trends are uncertain. What is certain, however, is that silica sand will continue to be banned in more and more countries until its absence is made universal. Metallic shot and grit will continue to dominate the market with aluminium oxide heading up the list of other abrasives. Although the natural minerals are hoping to make an impact on the market, slight doubts about availability may hinder them. In addition, being natural products they cannot always be guaranteed to be consistent, and fear of a free silica content may be a problem. There is little doubt that the industry has come a long way since the Victorian days of Mr. Tilghman, but its description as a 'black art' may still be applicable.

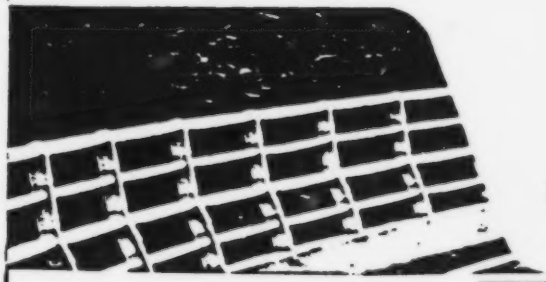
APPENDIX G

TAISEI NICKEL SLAG PAVEMENT [56]

G1 General Description.

G2 Chemical Analysis of Nickel Slag.

G3 Gradation of Nickel Slag.



Nickel Slag Pavement

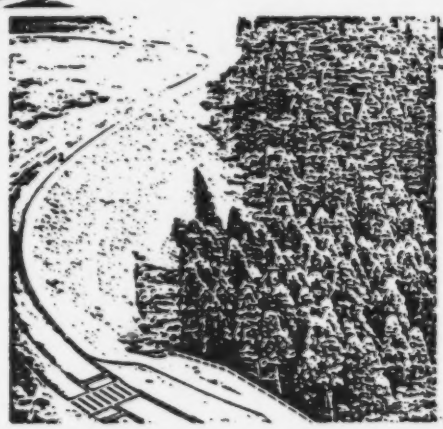
●ニッケルスラグ すべり止め舗装

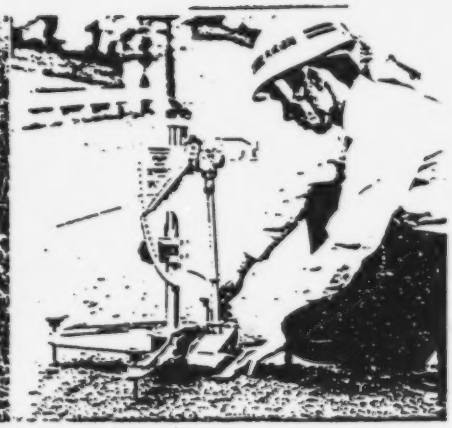
ニッケルスラグ
NICKEL SLAG

Anti-skid asphalt mixture which uses nickel slag.

Skid Resistance
Skid resistance is maintained constant by composite crystals of nickel slag.

Homogeneity
Quality of aggregates is homogeneous.

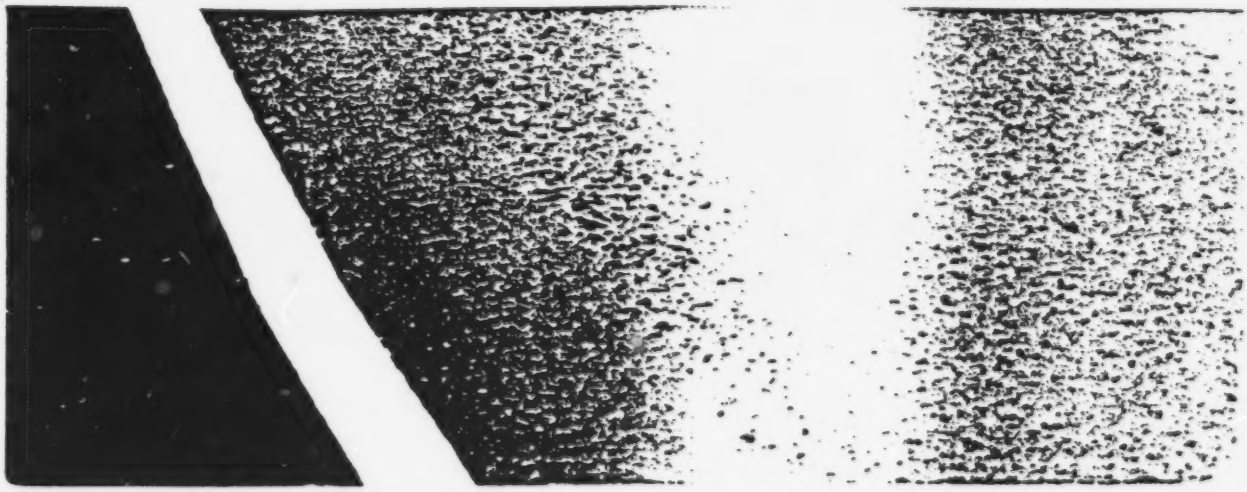




TAISEI ROAD CONSTRUCTION CO., LTD.

Head Office/Branches

Head Office 13-1, 3-Chome Kyobashi, Chuo-Ku, Tokyo 104 Tel. 03-561-7831
Telex 2522160 TAROAD J



No.

分析試験報告書

所長	部長	課次長	課長	係長	係

受付 50 年 9 月 3 日　　報告 50 年 10 月 13 日

試料名	テーリング・スラグ	試料採取場所		依頼者	ナス剛産(株)	受付番号	No.

	C%	SiO_2%	Fe%	Al_2O_3%	CaO%	MgO%	Ni%
9/3	0.04	54.34	5.49	2.64	4.71	29.71	0.25

(A)

日本冶金工業株式会社大江山製造所　研究部管理課分析係

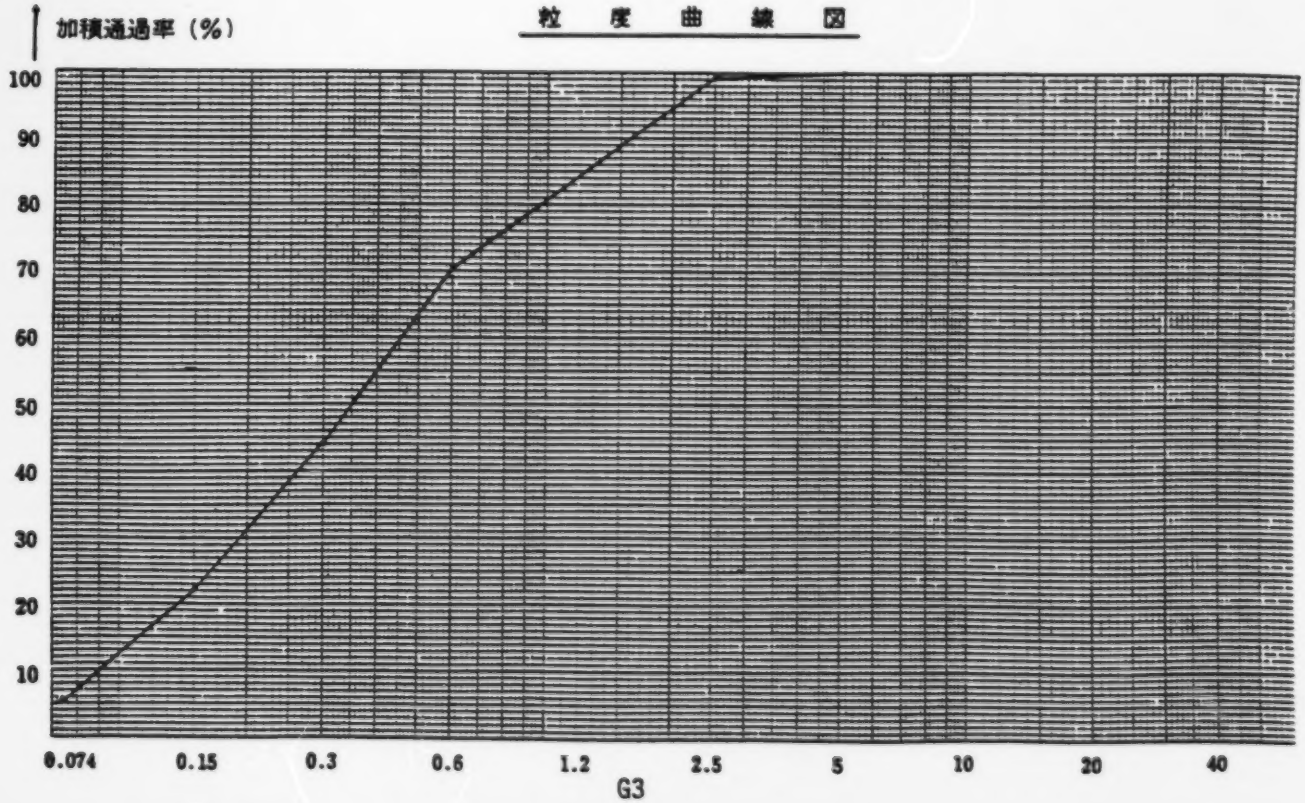
ふるい分け試験成績表

調査名目的 ＿＿＿＿＿＿＿＿＿＿　試験年月日 61年 8月19日

試　　料 ニッケルスラグ　試 験 者 ＿＿＿＿＿＿＿＿

フルイ寸法 (mm)	加積残留重量 (g)	加積残留率 (%)	加積通過率 (%)	加積残留重量 (g)	加積残留率 (%)	加積通過率 (%)	平均加積通過率 (%)
20							
13							
10							
5	0	0	100				
2.5	0.6	0.1	99.9				
1.2							
0.6	230.3	29.2	70.8				
0.3	440.3	55.8	44.2				
0.15	612.7	77.7	22.3				
0.074	747.3	94.8	5.2				
合　計	788.4	100.0	0				
備　考							

粒　度　曲　線　図



APPENDIX H

DATA SUPPLIED BY MANITOBA ROLLING MILLS AND IMS, SELKIRK

H1	Furnace Steel Slag Chemical Analysis, Melt In and Pre Tap, MRM.
H2	Ladle Steel Slag Chemical Analysis, MRM.
H3 to H9	Information on Mill and Steel Slag, IMS.
H10, H11	Steel Slag Aggregate Asphalt Paving Reports, City of Winnipeg.

Date FEB. 28, '85

MANITOBA ROLLING MILLS

A UNIT OF AMCA INTERNATIONAL LIMITED

SELKIRK, MANITOBA

CHEMICAL ANALYSIS

TREVOR JARVIS

Grade SLAG Analysis Customer TREVOR ELDERFIELD

Heat	C	Mn.	S	P	Si.	Cu.	V	Cb.	Cr.	Ni.	Mo.	Sn.	Al.	
		FeO		MnO		SiO_2		CaO		P_2O_5		MgO		
55320	M.I.	7.9		7.10		15.46		41.72		.28		7.31		
	P.T.	12.5		5.04		20.66		45.98		.19		12.33		
55334	M.I.	10.4		8.78		19.34		39.14		.49		9.22		
	P.T.	11.8		6.59		12.30		51.31		.51		11.02		
55347	M.I.	10.4		7.10		17.32		34.20		.69		15.40		
	P.T.	9.2		4.39		15.28		34.88		.60		15.36		*
55369	M.I.	9.5		6.97		15.64		49.68		.66		11.06		
	P.T.	14.5		4.52		10.96		49.90		.46		10.86		
55370	M.I.	11.4		6.20		13.20		42.73		.60		9.61		
	P.T.	13.6		5.42		9.86		45.08		.58		10.60		

* INSOLUBLE OXIDES PRESENT IN SAMPLE

MI — MELT IN

PT — PRE TAP.

Deerwood Press Ltd., A488

Spectrographer-

Quality Control Supervisor

H1

Date _____

MANITOBA ROLLING MILLS

A UNIT OF AMCA INTERNATIONAL LIMITED

SELKIRK, MANITOBA

CHEMICAL ANALYSIS

Grade LADLE SLAG Customer _____

Heat	C	Mn.	S	P	Si.	Cu.	V	Cb.	Cr.	Ni.	Mo.	Sn.	Al.	
	INIT	[illegible]		[illegible]		5.02		(2C		6[illegible]		M.C		
55370	PRE	9.7		4.51		20.68		44.97		.32		14.40		
	POST	1.4		1.81		23.00		49.45		.04		11.75		
	(AFTER STIRRING)													
55334	PRE	8.0		4.39		19.70		51.58		.35		13.72		
	POST	1.5		1.92		24.06		50.49		.04		12.15		
55337	PRE	4.5		4.78		13.60		40.28		.12		19.30		
	POST	0.5		.65		20.05		44.07		.05		13.31		
55367	PRE	4.4		2.71		14.65		55.96		.13		5.74		
	POST	0.5		.52		17.50		54.61		.04		7.71		
55370	PRE	10.7		4.78		11.85		49.42		.41		9.56		*
	POST	2.0		2.71		18.50		56.41		.10		10.35		

* INSOLUBLE OXIDES PRESENT IN SAMPLE

NOTE THE HIGH LIME

Deerwood Press Ltd., 4488

Spectrographer-

Quality Control Supervisor

H2

INTERNATIONAL MILL SERVICE

P.O. Box 390, L'Orignal, Ont. K0B 1K0

NORMAND GERVAIS

L'ORIGNAL (613) 675-2000
WHITBY (416) 668-4871
REGINA (306) 545-1322

May 26, 1986.

John Emery
Suite 107, 16 Four Seasons Place
Etobicoke, Ontario
M9B 6E7

Dear John,

Please find enclosed the information you requested on the M.R.M. slag.

1- H. Bruce Irvine
Plant Production Manager
204-269-6673

Trevor Jarvis
Works Manager
204-269-6673

2- Steel Making Information:

- Two small electric furnaces
- Slag 6-8- tons per heat collected in pots
- Annual capacity 300,000 tons.
- Portion of the slag is "falling Slag".

Slag Processing

- Magnetic Separator
- Triple Deck screen plant 5' X 16'
- 3 sizes made presently 0X3/4", 3/4X2", 2"+. >5"

3- Copy of research attached

It was found that the mill practice to add carbon to the slag causes same to turn to dust. The minus 200 meche in the 3/4" X 0 slag is in the 15 to 20% range.

Early in 1986, a rip rap test section was placed on the river bank in Selkirk with satisfactory results. This was a provincial government project.

We are presently working with the city of Winnipeg to use steel slag on trial basis in paving. It seems to be agreed that a bus stop will be done with 3/4" X 0 slag. In order to reduce the dust content of the slag, it was suggested that the bag house from the asphalt plant be used to bleed out some of the dust.

4- Samples should be picked up & sent on my next trip to M.R.M. in the week of June 2, 1986.

5- City of Winnipeg
Murray Cong
820 Elgin Avenue
Winnipeg
R3E 1B2

Manitoba Highway
Barry Rowley 204 945 3778
Fred Young 204-945-8982
Terry Williams 204-945-6982

I am planning to be in Winnipeg on the week of June 2nd. Possibly the 5th and 6th. I could change my schedule if needed.

Normand Gervais

NG/DL

• CONTRACT LABORATORIES

TECHNICAL SERVICE LABORATORIES
DIVISION OF BURGENER TECHNICAL ENTERPRISES LIMITED
1201 PEWSTER DRIVE, MISSISSAUGA, ONT. L4W 1A2
TELEPHONE: (416) 625-1544
TELEX 06-960215

CERTIFICATE OF ANALYSIS

SAMPLE(S) FROM: International Mill Service Inc.
P.O. Box 390
L'Original, Ontario K0B 1K0

Attention: Norm Gervais

SAMPLE(S) OF: SLAG

REPORT No. T-2392

Inv.#29864

I.C.A.P. PLASMA SCAN OF LEACHATE

MG/L

	Manitoba Rolling Mill Selkirk Manitoba
Silicon (Si)	0.8
Aluminum (Al)	130
Iron (Fe)	0.3
Calcium (Ca)	220
Magnesium (Mg)	0.2
Sodium (Na)	2.1
Potassium (K)	<5
Titanium (Ti)	<0.02
Manganese (Mn)	0.1
Phosphorus (P)	<0.1
Barium (Ba)	0.5
Chromium (Cr)	<0.02
Zirconium (Zr)	<0.02
Copper (Cu)	<0.02
Nickel (Ni)	<0.1
Lead (Pb)	<0.1
Zinc (Zn)	0.03
Vanadium (V)	<0.02
Strontium (Sr)	0.1
Cobalt (Co)	<0.02
Molybdenum (Mo)	<0.1
Silver (Ag)	<0.5
Cadmium (Cd)	<0.02
Beryllium (Be)	<0.02
Boron (B)	10

Samples, Pulps and Rejects discarded after two months

DATE Sept. 6/85 SIGNED _____

CTA

For any enquiries on this report, please contact Customer Service Department – Edith Anzil

• CHEMICAL RESEARCH AND ANALYSIS
• CONTRACT LABORATORIES

TECHNICAL SERVICE LABORATORIES
DIVISION OF BURGENER TECHNICAL ENTERPRISES LIMITED
1301 FEWSTER DRIVE, MISSISSAUGA, ONT. L4W 1A2
TELEPHONE: (416) 625-1544
TELEX 06-960215

CERTIFICATE OF ANALYSIS

SAMPLE(S) FROM: International Mill Service Inc.
P.O. Box 390
L'Original, Ontario K0B 1K0

Attention: Norm Gervais

REPORT No. T-2392

Inv.#29864

SAMPLE(S) OF: SLAG

DISTILLED WATER LEACH TEST

Leaching was done using an equivalent amount of sample to 25 g dry sample and 400 ml distilled water.

Extraction time was as stated below. The quantity of 0.5N CH_3COOH used for pH adjustment is indicated in the table below.

A blank was prepared using the same ratio of distilled water to 0.5N CH_3COOH.

Sample #	Moisture Content %	Extraction Time (hrs.)	50g Dry Equivalent (g)	ml of CH_3COOH	pH Initial	pH Final
2392-1	1.46	24	25	0	0	11.33
Blank	-	24	-	0	0	6.50

Samples, Pulps and Rejects discarded after two months

DATE September 6/85 SIGNED

CTA

For any enquiries on this report, please contact Customer Service Department – Edith Anzil

D.G. FLATT, P. ENG.
A.J. WOJTOWICZ

3777 Telephone 775-0383

THE NATIONAL TESTING LABORATORIES LIMITED

501-C WESTON STREET
WINNIPEG, MAN. R3E 3H4

Report on aggregate samples

Received from

Laboratory No. M-3358

For gradation analysis

Date October 21, 1985

Reported to International Mill Service, Inc.
P.O. Box 390, L'Original, ON K0B 1K0

Attn: Mr. Norm Gervais

The following test data was obtained on the two aggregate samples submitted to our laboratory on October 10, 1985.

Sieve Size	Percent Passing	
	Sample #1	Sample #2
3/4"	100.0	100.0
5/8"	99.5	98.5
1/2"	96.7	94.1
3/8"	92.1	86.4
1/4"	84.0	75.1
#4	76.6	66.5
#10	59.0	48.0
#20	45.7	37.4
#40	32.5	26.2
#80	24.1	18.9
#100	22.3	17.4
#200	16.3	12.2

THE NATIONAL TESTING LABORATORIES LIMITED

Don Flatt, M. Eng., P. Eng.

DF/ss

Encls.

October 31, 1985.

Mr. Bruce Irving,
Manitoba Rolling Mills,
27 Main street,
Selkirk, Manitoba.
R1A 1P6

Dear Sir:

Re: Slag Disposal - Manitoba Rolling Mills

Further to my letter of July 5, 1985, this is to inform you that the additional sampling and testing of the slag from Manitoba Rolling Mills are now completed. Contrary to the results from the preliminary testing, the recent results indicated that the leachate of the slag contain a very low level of chromium, in some samples less than the detectable level. The discrepancy in the results can be attributed to the procedure used in obtaining leachate during the preliminary testing. Since then the method has been standardized, an adoption of the U. S. Environmental Protection Agency standard.

Therefore, based on the recent results, the concern and recommendation expressed previously are no longer valid and this branch will have no objection to the usage of the slag from Manitoba Rolling Mills as a backfilling or ripraping material.

.../2

Should you have any questions on the above, please do not hesitate to contact me at 945-7014.

Yours truly,

C. Lee, P. Eng.,
Environmental Engineer,
Waste Management Section,
Environmental Control services.

CL/hc

c.c. Mr. Norm Gervais, International Mill Service.

c.c. Mr. R. Leslie Price, Secretary-Treasurer,
R. M. of St. Andrews.

c.c. [illegible],
Town of Selkirk.

c.c. Mr. Dave Bergman, Environmental Protection Service,
Manitoba District.

c.c. Mr. Ray Van Cauwenberghe, P. Eng.,
Dept. of Highways and Transportation.

THE CITY OF WINNIPEG

WORKS AND OPERATIONS DIVISION
OPERATIONS DEPARTMENT — EQUIPMENT AND MATERIAL SERVICES BRANCH
200 TECUMSEH STREET, WINNIPEG, MANITOBA R3E 2B2

ASPHALT PAVING REPORT SHEET

CODE: Martin & McHugh
PROJECT:

DATE: Sept. 5 86
TESTED BY: C.H.

ASPHALT BRIQUETTE	#11	#12	#13	#14	
WEIGHT OF BRIQUET IN AIR (A)	1280.1	1371.9	1421.9	1411.0	
WEIGHT OF BRIQUET IN WATER (B)	820.7	879.0	913.9	902.5	AVERAGES
VOLUME (A-B) (C)	459.4	492.9	509.0	508.5	
BULK SPECIFIC GRAVITY (A÷C)	2.7865	2.7833	2.7935	2.7748	
IMPERIAL SPECIFIC GRAVITY (X62.4)	173.88	173.68	174.32	173.15	
MARSHALL STABILITY (KN	15.43	20.21	18.50	20.54	
BRIQUET FLOW (.01")	14	14	14	16	
AIR VOIDS = M.T.D. - BRIQUET / M.T.D. x 100%	1.47	1.59	1.22	1.89	
V.M.A. = VOIDS + 100 x BRIQUET x SP.GR. BY WT. - % ABSORPTION / 1.011 / 100 - % ABSORPTION	414	467	459	447	

ASPHALT EXTRACTION

WEIGHT OF SAMPLE	1000
FILTER PAPER AFTER	29.1
FILTER PAPER BEFORE	27.1
WT. ON FILTER PAPER	2.0
WT. OF SAMPLE AFTER EXT.	943.4
TOTAL AGGREGATE LEFT	944.2
OIL CONTENT (by difference)	5.56

SIEVE ON EXTRACTED SAMPLE

SIEVE SIZE	WT. RETAINED	% RETAINED	% PASSING
5/8	39	4.1	95.9
1/2	105	11.1	88.9
3/8	220	23.3	76.7
#4	346	36.9	59.1
#8	512	54.2	45.8
#16	645	68.1	34.9
#30	707	74.9	25.1
#50	787.5	83.4	16.6
#100	839	88.8	11.2
#200	890	94.2	5.8
PAN	64.4	6.8	

MAXIMUM THEORITICAL DENSITY

SAMPLE NUMBER	3	4
WEIGHT MIX & FLASK	2407	2373
WEIGHT FLASK	1198	1202.5
WEIGHT MIX (A)	1209	1171
WEIGHT OF FLASK & WATER (B) AT 25°C	3309.5	3254.5
A&B	4518.5	4425.5
WT. OF FLASK, WATER & MIX (C)	4011	4091.5
(A&B)-C	507.5	334.0
M.T.D. = A / (A+B)-C	2.8282	2.9251
AVERAGE	176.68	176.29
		176.44

SUMMARY OF RESULTS

MARSHALL STABILITY	
FLOW INDEX (.01")	
BRIQUET DENSITY	
M.T.D.	
ASPHALT CONTENT	
AIR VOIDS	
VOIDS IN MINERAL AGGREGATE	
% VOIDS FILLED	

Batch Number	Briquet Number	Age of Asphalt	Temperature of Asphalt at Track	Weight of Oil	Weight of Filler	Time of Sample	Remarks

THE CITY OF WINNIPEG

WORKS AND OPERATIONS DIVISION
OPERATIONS DEPARTMENT — EQUIPMENT AND MATERIAL SERVICES BRANCH
200 TECUMSEH STREET, WINNIPEG, MANITOBA R3E 3B2

ASPHALT PAVING REPORT SHEET

CODE: _____
PROJECT: _____
DATE: Sept 7, 86.
TESTED BY: C.H.

ASPHALT BRIQUETS	4	5			AVERAGES
WEIGHT OF BRIQUET IN AIR (A)	1417.6	1358.5			
WEIGHT OF BRIQUET IN WATER (B)	895.5	859.6			
VOLUME (A-B) (C)	522.1	498.9			
BULK SPECIFIC GRAVITY (A÷C)	2.7152	2.7230			2.7191
IMPERIAL SPECIFIC GRAVITY (X62.4)	169.43	169.91			169.67
MARSHALL STABILITY (4500) K.N.	16.37 kN 4130 lbs	17.78 kN 4000 lbs			18.07 K.N.
BRIQUET FLOW (.01")	12.5	12			12
AIR VOIDS = M.T.D. - BRIQUET / M.T.D. x 100	2.15	2.87			3.01.
V.M.A. = VOIDS + 100 x BRIQUET / 1.018 x WT. BY WT. - % ABSORPTION / 100 - % ABSORPTION					

ASPHALT EXTRACTION	
WEIGHT OF SAMPLE	1200
FILTER PAPER AFTER	28.1
FILTER PAPER BEFORE	26.9
WT. ON FILTER PAPER	1.2
WT. OF SAMPLE AFTER EXT.	948.0
TOTAL AGGREGATE LEFT	949.2
OIL CONTENT vol	5.08

SIEVE ON EXTRACTED SAMPLE				
SIEVE SIZE	WT. RETAINED	% RETAINED	% PASSING	
3/8	76.5	8.1	91.9	
1/2	139	14.6	85.4	
3/8	226.5	23.9	76.1	
#4	435.5	45.9	54.1	
#8	547.5	57.3	42.7	
#16	639	67.3	32.7	
#30	726	76.5	23.5	
#50	775	81.6	18.4	
#100	827	86.6	13.4	
#200	878.5	92.7	7.3	
PAN 2/3	695	7.3		

MAXIMUM THEORITICAL DENSITY	
SAMPLE NUMBER	4
WEIGHT MIX & FLASK	2546
WEIGHT FLASK	1202.5
WEIGHT MIX (A)	1343.5
WEIGHT OF FLASK & WATER (B) AT 25°C	3254.5
A&B	4638.0
WT. OF FLASK, WATER & MIX (C)	4144.5
(A&B)-C	493.5
M.T.D. = A / (A+B)-C	2.7234
AVERAGE	174.93.

SUMMARY OF RESULTS	
MARSHALL STABILITY	
FLOW INDEX (.01")	
BRIQUET DENSITY	
M.T.D.	
ASPHALT CONTENT	
AIR VOIDS	
VOIDS IN MINERAL AGGREGATE	
% VOIDS FILLED	

MIX DESIGN NUMBER	BRIQUET NUMBER	AGE OF ASPHALT	TEMPERATURE OF ASPHALT OUT OF TRUCK	WEIGHT OF OIL	WEIGHT OF FILLER	TIME OF SAMPLE	REMARKS

APPENDIX I

STEEL SLAG UTILIZATION

I1 to I9 — Emery, J.J., "Steel Slag Utilization in Asphalt Mixes", Proceedings - 29th Annual Conference of Canadian Technical Asphalt Association, Saskatoon, Multiscience, Montreal, 1984. [71]

I10 to I13 — "Dense Friction Course Mix", OPS/Metric Special Provision No. 321 (Ontario Provincial Standard).

I14 to I18 — "Open Friction Course Mix", OPS/Metric Special Provision No. 311.

I19 — "Slag improves pavements skid resistance", Steel in Transportation No. 12, Stelco.

I20 — "Paving the way", Dofasco Illustrated News, Vol. 49, Issue No. 5/85.

I21, I22 — "Steel Slag Bituminous Mixes Provide Long Life and High Skid Resistance", MF 180-12, National Slag Association, Washington, 1980.

I23, I24 — "Steel Slag Required on the Illinois State Toll Highway", MF 185-1, National Slag Association, Washington, 1985.

I25 — Steel slag and asphalt, IMS.

I26 — Steel slag railroad ballast, IMS.

I27 — Chip sealing with steel slag, IMS.

I28 — Stabilize and surface with steel slag fines, IMS.

I29 Imsaskid steel slag fines for ice-control, IMS.

I30 Imsawall, IMS.

I31 "Comparison of Chemical and Physical Properties, Three Types of Steel Slag", MF 185-3, National Slag Association, Washington, 1985.

I32 "Determination of Free Calcium Oxide in Steel Slag by Ethylene Glycol Extraction", Recommended Procedure.

I33 "Slag", PennDOT Form 408 Section 703.3(a).

I34 to I39 PennDOT, "Method of Test for Evaluation of Potential Expansion of Steel Slags", Pa. Test Method No. 130, Commonwealth of Pennsylvania Department of Transportation, Harrisburg, Revised, May 1978. [74]

STEEL SLAG UTILIZATION IN ASPHALT MIXES

JOHN EMERY
President
John Emery Geotechnical Engineering Limited
Etobicoke

ABSTRACT

Steel slags are the major byproduct from the conversion of iron to steel in the basic oxygen (major type), electric arc and open hearth (minor type) steelmaking processes. Steel recovery from the slag results in a processed aggregate with both positive (wear resistant, skid resistant, rough textured, angular, well-graded, stripping resistant) and negative (heavy, expansive) features. Considerable experience, particularly since 1970 in Southern Ontario, has shown that the use of steel slag in asphaltic concrete minimizes potential expansion and takes advantage of the positive features in giving high stability, stripping resistant asphalt mixes with excellent skid resistance. (It should be noted that steel slag must not be used in confined applications or portland cement concrete.) The high stability of steel slag mixes offers a distinct advantage where rutting resistance is required and this has been demonstrated in industrial areas. The excellent skid resistance provided has been monitored in both urban and highway applications, and steel slag asphalt mixes (open and dense graded) are often used for critical pavements. While these positive applied features of steel slag asphalt mixes are emphasized, practical design guidance is also provided covering special features that must be dealt with to ensure satisfactory performance such as uniformity, deleterious materials, unit weight and potential expansion. It is clear that steel slag will continue to make a positive contribution to high quality asphalt mix aggregate requirements in areas of steel production.

ACKNOWLEDGEMENTS

The assistance of Stelco, Dofasco and the Ontario Ministry of Transportation and Communications with studies on the use of steel slag in asphalt mixes and their field performance is gratefully acknowledged. The author also wishes to thank Earl Kee of Red-D-Mix for the technical assistance and applications advice he has provided. Parts of this paper are based on an updating of an ASTM presentation on slag utilization in pavement construction.

INTRODUCTION

Since an earlier CTAA paper in 1973 on steel slag asphalt mixes [1] when there had been little use of such mixes in Canada, the use of steel slag in asphalt mixes has come of age in Southern Ontario with several suppliers of steel slag aggregate (Red-D-Mix, Steetley, Levy, IMS [2]) and applicable Ontario Ministry of Transportation and Communications (MTC) specifications for mixes such as dense and open graded friction courses [3,4]. The purpose of this paper is to review developments in steel slag asphalt mixes starting from a brief description of the range of slags available for use in pavement construction and maintenance [5].

Ferrous slags (iron blast furnace, steelmaking, foundry, ferro-alloy) are probably the industrial byproducts of greatest interest to pavement construction, given their fairly wide availability and scope of uses. Optimal uses appear to be in blended cements (ground slag and portland cement blend) for granulated blast furnace slag, and aggregate in asphaltic concrete for steel slags. In considering the use of ferrous slags, there are several important factors to note: pavement use is not new (iron slags were used during Roman road building in England); they are not wastes, but valuable byproducts processed for the construction industry; there is a continuing trend towards cementitious applications; and blast furnace slags (relatively low bulk density—typically 1300 kg/m³ for air-cooled—and stable with no expansion tendencies) must not be confused with steel slags (high bulk density—typically 1900 kg/m³—and potential expansive nature related to uncombined oxides) [6].

Iron blast furnace slag results from the fusion of fluxing stone with coke ash and the siliceous and aluminous residues remaining after the reduction and separation of iron from the ore. The blast furnace operation is a continuous process with the carefully controlled raw materials being fed in (burden) and the uniform products, molten iron and liquid slag, being drawn off at regular intervals. Selective cooling of the liquid slag results in four distinct types of blast furnace slag: (1) air-cooled (solidification under ambient conditions), which finds extensive use in conventional aggregate applications; (2) expanded or foamed (solidified with controlled quantities of water, sometimes with air or steam), which is mainly used as a lightweight aggregate; (3) granulated (solidified by quick water-quenching to a vitrified (glassy) state), which is mainly used in blended cement manufacture; and (4) pelletized (solidified by water and air-quenching in conjunction with a spinning drum), which is used both as a lightweight aggregate and in blended cement manufacture.

Nonferrous slags such as copper and nickel slag can be used in granular base and structural fill construction, and related applications such as ballast. Boiler slags are used in a number of applications such as seal coat, asphaltic concrete, and granular base construction. While most ferrous slag is utilized, there is still much scope to utilize nonferrous and boiler slags that are often disposed of with consequent environmental impact. With the present indications of materials and energy shortages, there is a new concern that all byproduct slags be utilized effectively [5].

STEEL SLAG PRODUCTION AND GENERAL PROPERTIES

While much steel slag from the various steelmaking processes (open hearth, basic oxygen, and electric arc) is suitable for return to blast furnace burden, there is still a large quantity available that can be effectively utilized in road construction. In considering steel slags, two points must be emphasized: there is typically a large variation in steel slags, even for the same plant and furnace; and the economic worth of steel slag for return to blast furnace burden and other potential applications such as fertilizer must be recognized. The various steelmaking processes generally introduce restrictions in the uses of steel slags in comparison

to blast furnace slags. Steel slags have a high bulk density and potential expansive nature (volume changes of up to 10 percent or more attributable to the hydration of calcium and magnesium oxides), while blast furnace slags have a relatively low bulk density and are stable. Since serious damage may result from indiscriminate use of steel slags in confined applications, potential long-term volume changes must be checked before such usage. Obviously, steel slags should not be used in portland cement concretes or related mix types such as lean concrete since expansion will result in rapid destruction of the concrete. However, there are many applications where expansion is tolerable, has been controlled by suitable aging or treatment, or where sealing of the steel slag with an asphalt cement coating eliminates any problems [5]. Further, the potential for selective use, based mainly on the free lime content, has been developed in some countries [7].

The expansive nature of steel slags can be traced back to the steelmaking process in which the conversion of pig iron to steel involves the controlled adjustment of various impurities, and the addition of small quantities of constituents that give special properties to the steel. Chemical compositions for typical Canadian open hearth and basic oxygen furnace steel slags are compared with those of blast furnace slag, the proportions are quite different, with the higher iron content being reflected in the high specific gravity of 3.2 to 3.5 for steel slag compared to 2.2 to 2.5 for air-cooled blast furnace slag. The mineral composition of steel slags is fundamentally different from blast furnace slags where the calcium and magnesium oxides are always combined in silicate and aluminosilicate minerals, and consists essentially of calcium silicates, calcium oxide-ferrous oxide solid solutions, oxides, and free lime. Steel slag phase compositions are similar to that of a weak portland clinker and, while the dicalcium silicate present is in the potentially metastable β form, it appears to be inactive. The calcium and magnesium oxides are not completely combined in steel slags, and there is general agreement in the literature that the hydration of unslaked lime (free CaO) and magnesium oxide (MgO) in contact with moisture is largely responsible for the expansive nature of most steel slags. The unslaked lime hydrates rapidly and can cause large volume changes in a few weeks. Magnesium oxide hydrates more slowly and contributes to the long-term expansion that may take several years to develop in the field, even when old steel slag dumps are being used.

TABLE 1 - *Chemical composition of iron blast furnace slags, portland cement, and steel slags* [6].

	Iron Blast Furnace Slag			Steel Slag	
Constituent, %	Usual Range	Typical	Portland Cement	Open Hearth	Basic Oxygen
Calcium oxide (Ca)	36–45	37.6	64.1	25.8	41.3
Silicon dioxide (SiO_2)	33–42	34.8	22.0	16.4	15.6
Aluminum oxide (Al_2O_3)	10–16	8.1	5.5	2.4	2.2
Magnesium oxide (MgO)	3–16	15.4	1.4	10.0	6.9
Iron (FeO or Fe_2O_3)	0.3–2	0.8	3.0	26.0	20.0
Sulfur (S)[a]	1–3	1.3	2.1[b]	..	..
Manganese oxide (MnO)	0.2–1.5	0.61	..	11.2	8.9
Titanium dioxide (TiO_2)	..	0.31	..	0.8	0.5
Free lime (free CaO)	..	0.47	..	2.1	3.3

[a] Principally as calcium sulfate.

[b] SO_3.

A separate problem that can occur with steelmaking slags is contamination with steel works rubbish such as refractories. Inevitably, some refractories get into the steel slag from furnace linings, but the major problem results from using ladles and pits as waste receptacles in the furnace areas. Fortunately, the value of steel slags is increasingly being recognized, particularly for return to blast furnace burden, and contamination is avoided. Small quantities of refractories do not appear to cause problems in highway applications. In addition to meeting specific coarse and fine aggregate gradations [3,4], for steel slag the MTC requires the total amount of non-slag constituents (furnace brick, incompletely fused fragments, lime, wood, rock, etc.) to not exceed 3 percent by mass and wood content alone to not exceed 0.5 percent by mass [4]. It should be noted that it is the lining material and incompletely fused fragments (i.e. free lime and/or magnesia) that are of particular concern, and the MTC requirements are under review.

Processing of steel slags for steel recovery is very important as it results in an angular, generally well-graded, material that is relatively free of metallics, and the recovered steel (2 to 4 percent of raw steel production) is a valuable scrap. It appears that improved, or even new methods for removing the steel from steelmaking slags would be highly desirable since this is a very space and time consuming activity. Slag modifications to lower the viscosity in the molten state, thus allowing the steel to separate, have been developed and patented, but not used commercially. Similar processes are being developed to give a steel slag suitable for cement manufacture. Since the steelmaking slags are reduced in size, and water is involved during processing, it is likely that hydration of calcium oxide occurs and the aging process is accelerated. Processed steel slag is still high in iron, lime, and manganese, so that it is possible to return steelmaking slag (particularly the large sizes) to blast furnace burden.

EXPANSION TESTS

There is a large amount of steel slag used for applications such as bases, and many old steel slag heaps or fills are being built on, or used for construction purposes. It is critical that these steel slags be checked for potential expansion, since even aging for long periods in large dumps does not guarantee the elimination of expansive behaviour (particularly if unprocessed so large lumps are involved). Leachates are not considered a problem from the typical data in Table 2 and Trow Ltd testing.

TABLE 2 - *Typical ferrous slag solubility test data (Calspan Corporation for Environmental Protection Agency)* [5].

Slag	Analysis of Filtrate, mg/l[a,b]						
	Cr	Cu	F	Mn	Pb	Zn	pH
Blast furnace (iron)	<0.01	<0.03	1.9	<0.01	0.20	<0.01	10.6
Open hearth (steel)	0.01	0.04	3.1	<0.01	0.30	<0.01	12.5
Basic oxygen (steel)	0.03	0.03	4.0	<0.01	0.20	<0.01	12.5
Electric arc (steel)	0.27	0.03	1.5	<0.01	0.44	<0.01	12.4
Iron and steel foundry	0.05	0.25	ND[c]	0.06	<0.20	0.12	10.6
Ferrochrome	0.02	0.02	ND	0.30	0.40	0.20	9.9
Ferronickel	0.01	0.74	ND	0.07	1.00	2.00	8.5
Silicomanganese	<0.01	0.17	ND	0.10	<0.20	0.05	6.8
Ferromanganese	0.02	0.04	ND	2.10	<0.20	0.03	5.9

[a]One solubility test for each slag. Two parts distilled water (pH 5.5) to one part slag gently agitated for 72 h. Mixture filtered through 0.45 um micropore and filtrate analyzed. Selected samples probably represent the more comminuted fraction of slag. Ni <0.05 mg/l for all slags and Co <0.02 mg/l for ferronickel slag.

[b]All ferrous slags listed considered non-hazardous. (Toxic materials not leached at greater than 1 mg/l. Greater tolerances for F, Mn, and Zn.)

[c]ND = not determined.

It was considered desirable to develop a simple, economical, and rapid test procedure for evaluating the expansion potential of steel slags [8]. The procedure adopted involves preparing steel slag specimens and a non-expansive control using the Standard Proctor method and stainless steel molds with perforated base plates to allow for moisture movement during the immersion period. The specimens are then totally immersed in a water bath at 82 ± 1°C and the vertical expansion with time monitored. Since the expansion levels of 5 to 9 percent observed at 82°C (about three times that at 60°C) are similar to the levels of long-term expansion often observed in the field, this test temperature was adopted. A short monitoring period of one to seven days appears adequate to detect potential expansive behaviour. The actual steel slag gradation involved for a project should be tested since the expansive behaviour is clearly a function of gradation. Also, surcharge weights to simulate overburden conditions can be used.

Tests have indicated that aging in stockpiles (preferably after processing and in small quantities), spent acid treatments, and the use of coarser sizes all tend to limit the potential expansion of steel slags. These results are in qualitative agreement with field observations. It should be noted that aging steel slag in large heaps or pieces is not very effective, as steel slag remains expansive for extremely long periods if not directly exposed to weathering. This expansion potential monitoring procedure for steel slags has been improved and adopted by the Pennsylvania Department of Transportation (Penn DOT) as PTM 130 with two major modifications: the test temperature has been reduced to 71 ± 3°C; and the test involves 7 days fully submerged followed by 7 days unsubmerged but saturated at 71 ± 3°C [9]. Penn DOT uses this test for the acceptability of steel slag Type C aggregate under strict conditions.

> "Type C aggregate may be crushed and prepared from tough, hard, durable pieces of steel slag and shall be reasonably uniform in density and quality. After gradation preparation, steel slag coarse aggregate, whether re-claimed from an old stockpile or processed directly from the steel making process, shall be placed in a controlled stockpile initially in a fully saturated condition. The method of constructing and controlling the stockpile during the cure period shall be submitted to the engineer for his review. The slag shall then be kept in a reasonably uniform moist condition in the stockpile for a period of not less than 6 months in which the average monthly temperature is above 40°F. After this minimum cure period, the stockpile shall be sampled by the engineer and the slag shall be tested by the BMTR for expansive characteristics in accordance with PTM 130. The steel slag stockpile will only be approved for use if the average volumetric expansion by PTM 130 is less than 0.50 percent. If the stockpile does not pass this expansion criterion for its use, it shall not be re-sampled and re-tested until a minimum additional cure period of 2 months from the time of the last sampling has elapsed. Steel slag aggregate may only be approved for use in the construction of modified subbase, subbase, selected material surfacing or stabilized shoulders. Approved steel slag may be blended with other approved aggregates to uniformly and consistently maintain the grading required for the specified item of construction." [9]

It is recommended that this Penn DOT requirement, and related test procedure, be adopted by contractors or agencies considering the use of steel slag for granular subbase, unless satisfactory performance can be demonstrated by other means.

STEEL SLAG AGGREGATE FOR ASPHALT MIXES

The discussion in the previous section was concerned with the potential expansion of steel slag that has not been coated with asphalt cement. As indicated in following sections, the use of steel slag in asphaltic concrete results in an excellent product, and the processing involved and asphalt cement film coating the steel slag limits potential expansion. However, the question still often arises concerning the need for aging steel slag prior to use in asphaltic concrete, and there have been a few cases of surface pop-outs and/or ravelling related to over-size and/or excess deleterious limey material. These problems appear to be related to a lack of attention during processing. General experience indicates that if the finer steel slag sizes are used (minus 13.2 mm) and contamination is avoided at the sleel works, aging is not critical prior to use in asphaltic concrete. If tighter quality control of steel slag aggregate for use in asphaltic concrete is considered necessary, the following suggested requirements should be considered with suppliers: contamination by refractories and rubbish to be avoided at the steel slag processing area; a minimum weathering period of one month following steel slag processing to be completed before screening; a minimum of 5000 tonnes of weathered and screened steel slag (coarse and fine) to be developed and maintained before shipment to ensure gradation and composition consistency; free lime content of weathered steel slag to be monitored (ethylene glycol extraction, for instance) and average not to exceed a specified percentage (this level has not been established, but is probably in the six percent range); and any agglomerated and/or crusted stockpiled steel slag (coarse and fine) to be re-screened. It should be noted that avoiding under-asphalted mixes and ensuring adequate mixing is also important to achieving desired steel slag asphaltic concrete pavement performance.

FEATURES OF STEEL SLAG ASPHALTIC CONCRETE FOR MUNICIPAL, HIGHWAY AND INDUSTRIAL PAVEMENTS

Steel slag has been used in binder and surface course asphaltic concrete mixes in the Hamilton-Toronto area since 1969, with a large growth in use the past five years related to both its general acceptance for municipal street work and increasing MTC highway application in dense graded friction course (skid resistance) and open graded friction course (skid resistance and tire-pavement noise reduction) [5,11,3,4]. This growth in steel slag asphaltic concrete use and friction course applications have given Ontario world leadership. Steel slag is also used in hot mix for winter patching with several advantages being demonstrated: fairly dry so heating costs reduced; retains its heat very well; and the high unit weight and stability tends to hold patches in place. Steel slag asphaltic concrete has been found to be excellent for industrial and heavy duty applications. While it has been possible to develop steel slag slurry seal mixes in the laboratory, field experience to-date indicates the inherent variability of steel slag aggregate (particularly free lime content) limits this potential application. Steel slag use in surface treatments (cover chips and coated chippings) should grow as it has been developed in other areas and recently demonstrated by Dofasco/Red-D-Mix.

Typical conventional gradation requirements for steel slag use in asphaltic concrete mixes are given in Table 3, and the MTC have developed specific requirements for friction course mixes [3,4]. Marshall method characterization of typical steel slag asphaltic concrete mixes, as summarized in Table 4, indicates the following general features: they are designed in the same way as any other mixes and no problems have been experienced in meeting relevant specifications; they combine very high stabilities (1½ to 3 times greater than most other mixes) with good flow properties, resulting in a mix that resists rutting after cooling, but is still compactible; they have excellent resistance to stripping of asphalt cement from the steel slag as anticipated from the free lime contents of Table 1; and they have bulk densities 15 to 25 percent greater than most conventional mixes that

can result in a cost disadvantage on a volumetric basis. The high stability of steel slag asphaltic concrete mixes offers a distinct advantage for applications where rutting resistance is required, such as industrial roads and parking areas subjected to heavy axle loads. Resilient moduli research by the author [12] has shown that the resilient modulus (M_r) values of steel slag asphaltic concrete tend to be some 20 to 80 percent higher than for conventional mixes at typical design temperatures (29°C). Also, steel slag asphaltic concrete mixes have relatively lower resilient Poisson's ratio (ν_r) values than most conventional mixes. As high ν_r values at elevated temperatures are an indicator of deformation susceptibility, the lower steel slag asphaltic concrete ν_r values support the observation that these mixes typically demonstrate high in-service stability and rutting resistance. The higher stability of steel slag asphalt mixes and resilient moduli values can be used to design thinner steel slag asphaltic concrete pavements on both an empirical and rational basis.

TABLE 3 - *Typical gradation requirements for steel slag*[a]

Coarse Aggregate	
Sieve	Percent Passing
16.0 mm	100
13.2 mm	96-100
9.5 mm	50-73
4.75 mm	0-10
Fine Aggregate	
Sieve	Percent Passing
9.5 mm	100
4.75 mm	90-100
2.36 mm	72-100
1.18 mm	50-90
600 µm	32-70
300 µm	14-40
150 µm	5-15
75 µm	0-5

a. MIC Form 1003, August, 1981, HL1 and HL3 requirements

TABLE 4 - *Typical properties of steel slag asphaltic concrete mixes (13.2 mm top size steel slag aggregate)*

Marshall Designs[a]	
Property of laboratory compacted mix	Range
Stability (kN)	16-22
Flow index (mm)	4.0-5.5
Voids in mineral aggregate (%)[b]	17-19
Air voids (%)	3-4
Asphalt cement content (%)[c]	5.5-6.0
Bulk density	2.85-2.90
Immersion-Marshall Stripping Test Results[a]	
Retained stability (%)	75-85
Stripping rating number[d]	3-4

a. Testing in accordance with MIC Laboratory Manual.
b. Uncorrected (i.e. not saturated surface dry).
c. Percent by weight of total mix.
d. A stripping rating number of 3 indicates no stripping, of 4 indicates slight stripping, etc.

SKID RESISTANCE OF STEEL SLAG ASPHALTIC CONCRETE

Experience with steel slag asphaltic concrete in several countries indicating very satisfactory skid resistance for most applications has also been demonstrated in Ontario. During 1974, the MTC constructed 17 asphaltic concrete test sections on Highway 401 (Toronto bypass section) to evaluate methods for improving rigid pavement skid resistance with thin overlays. Extremely high traffic volumes are involved with a total daily traffic of 199 000 (1976) using a twelve lane collector and express lane system. Dense graded surface course mixes, dense graded friction course mixes and open graded friction course mixes were placed using limestone, traprock, steel slag and air-cooled blast furnace slag aggregates, or combinations. These test sections have yielded valuable general information on the skid resistance for high traffic volume conditions: initial target skid numbers must be substantially greater than recommended minimum levels; early decline in skid resistance is due to coarse aggregate immersion into the matrix under wheel loads; dense and open graded mixes of 100 percent crushed aggregates with fairly high PSV (traprock, steel slag and blast furnace slag – PSV greater than about 40 to 50), and high stability, provide skid numbers close to, or above, recommended minimum levels; crushed fines result in much better macrotexture than mixes containing sand; and adequate macrotexture is achieved when the stone projection above the matrix is 0.5 mm, or greater. It is clear that factors contributing to high mix stabilities are important to maintaining skid resistance. Continuing monitoring also shows that the skid numbers have levelled off rather than continuing to decrease at a reduced rate. Weathering influences, which are generally seasonal and particularly demonstrated by steel slag, appear to be regenerating microtexture at about the same rate that traffic polishing is involved [13,14].

Polished stone values (PSV, high values desirable) and aggregate abrasion values (AAV, low values desirable) summarized in Table 5 [14] support the general finding that the all-steel slag and all-blast furnace slag mixes have shown the best skid resistance performance of the Highway 401 sections. Also, a study of skid resistance in the urban context has shown that steel slag asphaltic concrete mixes appear to provide superior skid resistance to other mixes. The wet road accident rate did not significantly exceed the dry road accident rate for steel slag asphaltic concrete surfacings, while the reverse was generally true of other surfacings.

TABLE 5 - *Typical PSV and AAV values for aggregates [14]*

Aggregate	PSV	AAV
Steel slag	55 to 59	2 to 4
Blast furnace slag	54	14
Sandy dolomite	53	4
Granite	45 to 47	–
Traprock	45	2
Igneous and metamorphic gravel	43 to 47	–
Quartzite	42	–
Limestone	41 to 45	8

Based on highway, laboratory, and urban studies, it appears that steel slag asphaltic concrete mixes of adequately coarse gradation provide satisfactory skid resistance for most applications. Indeed, for Ontario, they appear to be the most skid resistant aggregate currently available and are included in the MTC specifications [3,4].

CONCLUSIONS

From the previous discussion, it is possible to indicate the demonstrated applications for steel slag asphalt mixes in order of relative merit: surface course mixes that take advantage of the excellent skid resistance and good wear resistance of steel slag asphaltic concrete; industrial paving where the high stability and consequent rutting resistance is an important asset; winter patching; and binder courses where some depth reduction related to higher resilient moduli is possible. It would appear there is scope for using steel slag as chips in surface treatments that should be developed to take advantage of its skid resistance and quickly achieved stability.

REFERENCES

1. Emery, J.J., Drysdale, R.G. and Nicholson, P.S., Steel Slag Asphalt Mixes, Proceedings, Canadian Technical Asphalt Association, Vol. 18, 1973.

2. MTC, Designated Sources for: Aggregates, Coarse - HL1, DFC, DS:102, Ontario Ministry of Transportation and Communications.

3. MTC, Dense Friction Course Mix, Special Provision No. 321, Ontario Ministry of Transportation and Communications, June, 1983.

4. MTC, Open Friction Course Mix, Special Provision No. 311, Ontario Ministry of Transportation and Communications, January, 1983.

5. Emery, J.J., Slag Utilization in Pavement Construction, Extending Aggregate Resources, ASTM STP 774, American Society for Testing and Materials, 1982.

6. Emery, J.J., Slags as Industrial Minerals, Proceedings, Third Industrial Minerals International Congress, Metal Bulletin Group, London, 1978.

7. Rellermeyer, H.M. and Maas, H.G., Utilization of BOS Slags at August Thyssen Hütte AG, Annual Open Hearth Steelmaking Conference, Toronto, 1975.

8. Emery, J.J., A Simple Test Procedure for Evaluating the Potential Expansion of Steel Slag, Selected Workshop Papers, Roads and Transportation Association of Canada, 1974.

9. Penn DOT, Method of Test for Evaluation of Potential Expansion of Steel Slags, Test Method No. 130, Pennsylvania Department of Transportation, June 1976, Revised May 1978.

10. Penn DOT, Proposed Changes to Penn DOT Form 408 703.3(a) 3. Slag, Form 408, Pennsylvania Department of Transportation.

11. Lewis, D.W., Resource Conservation by Use of Iron and Steel Slags, Extending Aggregate Resources, ASTM STP 774, American Society for Testing and Materials, 1982.

12. Emery, J.J., Characterization of Flexible Pavement Components, Proceedings, Paving in Cold Areas, Vol. 2, 1982.

13. Emery, J.J., Lee, M.A. and Kamel, N., Skid Resistance Predictive Models for Asphaltic Concrete Surface Courses, Pavement Surface Characteristics and Materials, ASTM STP 763, American Society for Testing and Materials, 1982.

14. Emery, J.J., Skid Resistance Requirements and Predictive Models for Asphaltic Concrete Surface Courses, RTAC Forum, Vol.5, No.3, 1983.

DENSE FRICTION COURSE MIX - Item No

Dense friction course mix shall meet the requirements of HL 1 as specified in OPSS 310 except as follows:

Aggregates

The coarse and fine aggregates shall be obtained from the traprock or slag sources on the List of Designated Sources for HL 1 and DFC coarse aggregates. The coarse aggregate shall meet the gradation and physical requirements for HL 1, as specified in OPSS 1003. The fine aggregate shall meet the following gradation requirements:

MTC SIEVE DESIGNATION	PERCENT PASSING (BY MASS)	PERMISSIBLE**** PERCENT TOLERANCE
9.5 mm	100	± 5
4.75 mm	85 -100	± 4
2.36 mm	50 - 80	± 4
1.18 mm	25 - 60	± 4
600 µm	15 - 40	± 4
300 µm	10 - 25	± 4
150 µm	(5 -12)* (5-15)** (5-20)***	± 4
75 µm	(2-6.5)* (2- 8)** (2-15)***	± 2

* Where the aggregates is obtained from Electric Steel Slag or Blast Furnace Slag sources.

** Where the aggregate is obtained from Open Hearth or Basic Oxygen Furnance Steel Slag sources.

*** Where the aggregate is obtained from Traprock sources.

**** The fine aggregate once established by mix design shall be within the percentage passing (by mass) as per the table above and shall not exceed the permissible tolerances on any sieve.

The coarse and fine aggregates don not have to be obtained from the same source.

Physical Requirements for Coarse Aggregate

Steel slag shall not be required to meet the Absorption by Weight and Petrographic Number requirements of Table 3, OPSS 1003.

The total amount of non-slag constituents, such as furnance brick, incompletely fused fragments, lime, wood, rock, etc., in steel slag shall not be more than 3 percent by mass, and the wood content alone shall not be more than 0.5 percent by mass.

Asphalt Cement

***** DESIGNER'S OPTION A

a) Supply: - The Authority will supply up to 4.5 percent asphalt cement (by mass) for the equivalent tonnage of traprock mix; the Contractor shall supply any additional asphalt cement required, depending on the

aggregates selected by the Contractor, up to the percentage shown in Table 1 below for the aggregate combination utilized. The Authority will provide any asphalt cement required beyond the percentage shown for the combination utilized.

****** DESIGNER'S OPTION B

a) Supply: - The Contractor shall supply up to 4.5 percent asphalt cement (by mass) for the mix based on traprock coarse and fine aggregates. If additional asphalt cement is required because the Contractor chooses aggregated other than traprock coarse and fine aggregates the additional asphalt cement in excess of 4.5 percent shall be supplied by the Contractor at his own cost.

If the percentage of mass of asphalt cement in the desired mix, as specified by the Authority, differs from those specified in Table 1, and if the Contractor chooses to supply traprock coarse and fine aggregates, the price bid per tonne of hot mix shall be adjusted upwards or downwards by an amount of 0.1 percent of the price of the asphalt cement used in the mix for every 0.1 percent increase or decrease respectively in the asphalt cement proportion in the desired mix. The price adjustment shall apply to the tonnage of hot mix, which has been placed using the revised "desired mix". The change in the desired mix shall be made upon written instructions by the Authority. The Contractor shall inform the Authority in writing of the purchase price of the asphalt cement.

The Authority will not allow any adjustments if the Contractor chooses to supply aggregate combinations other than traprock coarse and fine aggregates.

Asphalt cement shall be ****** grade conforming to OPSS 1101.

b) Content: - Regardless of the type of aggregates used, the quantity of asphalt cement required is determined by multiplying the asphalt cement content specified in the contract by the actual mass of hot mix placed.

Mix Proportions and Characteristics

The approximate coarse and fine aggregate proportions (by volume) for the dense friction course mix are:

Roadway Mix

Retained 4.75 mm sieve 55%
Passing 4.75 mm sieve 45%

Bridge Deck Mix

Retained 4.75 mm sieve 45%
Passing 4.75 mm sieve 55%

The approximate densities for the various combinations of aggregates experienced by the Authority, as detailed in Table 1, are provided for Contractor's information only. The Authority will not accept responsibility for material variability.

TABLE 1 ROADWAY MIX

Coarse Aggregate	Fine Aggregate	% A.C. (By Mass)	Approx. Density kg/m²/10mm Thickness @ 96% of Laboratory Marshall Density
Traprock	Traprock	4.5	27.0
Traprock	Steel Slag	5.4	28.0
Traprock	Blast Furnace Slag	6.0	24.3
Steel Slag	Steel Slag	5.7	28.5
Steel Slag	TrapRock	5.1	28.0
Steel Slag	Blast Furnace Slag	6.1	26.0
Blast Furnace Slag	Blast Furnace Slag	8.6	21.3
Blast Furnace Slag	Steel Slag	7.0	24.4
Blast Furnace Slag	Traprock	5.3	23.2

TABLE 1 - BRIDGE DECK MIX

Coarse Aggregate	Fine Aggregate	% A.C. (By Mass)	Approx. Density kg/m²/10mm Thickness @ 96% of Laboratory Marshall Density
Traprock	Traprock	4.5	25.9
Traprock	Steel Slag	5.8	27.1
Traprock	Blast Furnace Slag	6.2	25.1
Steel Slag	Steel Slag	5.8	28.5
Steel Slag	Traprock	5.1	27.0
Steel Slag	Blast Furnace Slag	6.3	25.5
Blast Furnace Slag	Blast Furnace Slag	8.6	22.9
Blast Furnace Slag	Steel Slag	7.2	24.6
Blast Furnace Slag	Traprock	5.5	23.9

The actual mix proportions, asphalt cement content and density, shall be determined by mix design. The Marshall void content of the mix shall be set at 2.5%.

Mix Distribution

The tonnage shown in the tender is based on a combination (by volume) of 55 percent traprock coarse and 45 percent traprock fine aggregates for Roadway Mix and 45 percent traprock coarse and 55 percent traprock fine aggregates for Bridge Deck Mix. If an of the other specified types and combinations are used, the tonnage of actual mix placed shall be adjusted for the density difference so that the specified course thickness is maintained.

Sampling and Testing

The Contractor shall demonstrate his ability to produce the desired mix before the initial placement of surface course on the contract. This shall be done at the plant by the Authority sampling and testing from a minimum of 5 tonnes of mix for drum and continuous mix plants or from a minimum of 2 batches of the size which will be used for batch plants.

Testing shall take approximately 4 hours. After the testing period, the Contractor may start placing hot mix on the road contract, providing the test mix is satisfactory. If the test mix is unsatisfactory, corrections shall be made and the testing procedure repeated.

Disposal of the hot mix material produced for the trail mix not used for testing shall be the responsibility of the Contractor and shall not be included in the work.

Acceptable trial test results do not negate the liability of the Contractor for hot mix placed subsequently elsewhere on the contract.

Trial Area

A surface course trial area will not be required for the Dense Friction Course.

Measurement for Payment

The payment quantities indicated on the tender are based on the mixes consisting of traprock aggregates only. The quantity for payment shall be determined by multiplying the total measured mass of the Dense Friction Course mix incorporated into the work by the appropriate factor given in Table 2 below, depending on the aggregate combination supplied.

TABLE 2 ROADWAY MIX

Coarse Aggregate	Fine Aggregate	Multiplying Factor
Traprock	Traprock	1.000
Traprock	Steel Slag	0.964
Traprock	Blast Furnace Slag	1.111
Steel Slag	Steel Slag	0.947
Steel Slag	Traprock	0.964
Steel Slag	Blast Furnace Slag	1.038
Blast Furnace Slag	Blast Furnace Slag	1.268
Blast Furnace Slag	Steel Slag	1.107
Blast Furnace Slag	Traprock	1.164

TABLE 2 BRIDGE DECK MIX

Coarse Aggregate	Fine Aggregate	Multiplying Factor
Traprock	Traprock	1.000
Traprock	Steel Slag	0.956
Traprock	Blast Furnace Slag	1.032
Steel Slag	Steel Slag	0.909
Steel Slag	Traprock	0.959
Steel Slag	Blast Furnace Slag	1.016
Blast Furnace Slag	Blast Furnace Slag	1.131
Blast Furnace Slag	Steel Slag	1.053
Blast Furnace Slag	Traprock	1.084

DESIGNER'S NOTES: ***** Use Option A when the Authority supplies asphalt cement.

Use Option B when the Contractor is to supply the asphalt cement.

****** Indicate penetration grade of asphalt cement whenever Option B is applied.

WARRANT: Always with this tender item.

OPEN FRICTION COURSE MIX - Item No.

Description

This special provision covers the requirements for Open Friction Course (O.F.C.) mix.

General Requirements

Open Friction Course mix shall meet the requirements for HL 1 as specified in OPSS 310 except as otherwise stated in this special provision.

Materials

Aggregates

The fine aggregate shall be washed screenings. The raw material or coarse and fine aggregates shall be obtained from sources listed on the Supplementary Aggregate Sources List for Open Friction Course Mix. The coarse and fine aggregates shall be obtained from the same source and they shall meet the following gradation requirements:

Coarse Aggregate

M.T.C. Sieve Designation	Percentage Passing
13.2 mm	100
11.2 mm	95 - 100
9.5 mm	85 - 100
6.7 mm	20 - 50
4.75 mm	0 - 15
75 µm	0 - 2 (0 - 1 for gravel)

Fine Aggregate

M.T.C. Sieve Designation	Percentage Passing
9.5 mm	100
4.75 mm	85 - 100
2.36 mm	50 - 70
1.18 mm	25 - 45
600 µm	10 - 30
300 µm	10 - 20
150 µm	0 - 10
75 µm	0 - 3

Physical Requirements for Coarse Aggregate

Steel slag shall not be required to met the Absorption by Weight and Petrographic Number requirements of Table 3, OPSS 1003.

The total amount of non-slag constituents, such as furnace brick, incompletely fused fragments, lime, wood, rock, etc., in steel slag shall not be more than 3 percent by mass and the wood content alone shall not be more than 0.5 percent by mass.

Asphalt Cement

* DESIGNER'S OPTION A

a) Supply - The Authority will supply up to 5.2 percent asphalt cement (by mass) for the equivalent tonnage of steel slag mix; the Contractor shall supply any additional asphalt cement required, depending on the aggregates selected by the Contractor, up to the percentage shown below for the aggregate combination utilized. The Authority will provide any asphalt cement required beyond the percentage shown for the combination utilized.

Origin of Raw Material For Aggregates	% A.C. (By Mass)
Steel Slag	5.2
Quarried Trap Rock	5.0
Gravel	5.3

* DESIGNER'S OPTION B

a) Supply - The Contractor shall supply up to 5.2 percent asphalt cement (by mass) for the equivalent tonnage of steel slag mix. If additional asphalt cement is required because the Contractor chooses aggregates other than steel slag coarse and fine aggregates, the additional asphalt cement in excess of 5.2 percent shall be supplied by the Contractor at his own cost.

If the percentage of mass of asphalt cement in the desired mix, as set by the Authority, differs from that specified above, and if the Contractor chooses to supply steel slag coarse and fine aggregates, the price bid per tonne of hot mix shall be adjusted upwards or downwards by an amount of 0.1% of the price of asphalt cement used in the mix for every 0.1% increase or decrease respectively in the asphalt cement proportion in the desired mix. The price adjustment shall apply to the tonnage of hot mix, which has been placed using the revised "desired mix". The change in the desired mix shall be made upon written instructionsby the Authority. The Contractor shall inform the Authority in writing of the purchase price of the asphalt cement.

b) Content - Regardless of the type of aggregates used, the quantity of asphalt cement required is determined by multiplying the Asphalt Cement content specified in the contract by the actual mass of hot mix placed.

Asphalt cement shall be ** grade meeting the requirements of OPSS 1101.

Mix Proportions

The approximate coarse and fine aggregate proportions by mass for the Open Friction Course mix are:

65% - 70% retained on 4.75 mm sieve
30% - 35% passing the 4.75 mm sieve

The actual proportions shall be determined by mix design. The quantity of asphalt cement required is determined by multiplying the Asphalt Cement content specified in the contract by the actual mass of the Open Friction Course mix placed. The approximate field densities for various aggregates experienced by the Authority are as follows:

TABLE 1

Origin of Raw Material For Aggregates	Approx. Density kg/m^2/10mm Thickness at 96% of Laboratory Marshall Density
Steel Slag	25.5
Quarried Trap Rock	23.0
Gravel	21.2

Mix Distribution

The tonnage shown in the tender is based on a combination of steel slag coarse and fine aggregates. If traprock or gravel aggregates are used, the tonnage of actual mix placed shall be adjusted for density difference so that the specified course thickness is maintained.

Mix Production

The mix shall be produced in a batch plant.

Hot Mix Storage Bins

The use of hot mix storage bins for storing or manufacturing this mix shall not be permitted.

Pavers

All pavers shall be equipped with either tamper bars or vibratory screeds.

Construction

Preparation and Placement of the Mixture

If the mixing plant is equipped with a dust collector system, which discharges directly into the boot of the hot elevator, such a system shall be purged of any fines accumulated from other previous production, before any Open Friction Course (O.F.C.) mix is manufactured. This procedure will take approximately two (2) hours to complete.

The temperature of the O.F.C mix, at discharge from the asphalt plant, shall not exceed 140° C.

The O.F.C. mix shall be placed within one hour of discharge from the asphalt plant. The air temperature for placement of O.F.C. mix shall be 12° C minimum.

The Contractor shall provide an on-site dump area where, at the direction of the Authority Inspector, vehicle boxes shall be cleaned of all deleterious material immediately after the discharge of O.F.C. Mix.

Sampling and Testing

The Contractor shall demonstrate his ability to produce the desired mix before the initial placement of surface course on the contract. This shall be done at the plant by sampling and testing from a minimum of two batches of the size which will be used. Testing will take approximately two hours. After the testing period, the Contractor may start placing the mix on the road providing the test mix is satisfactory. If the test mix is unsatisfactory, corrections shall be made and the testing procedure repeated.

Trial Area

A surface course trial area will not be required for the Open Friction Course mix.

Compaction of Mixture

Compaction of the mix shall be with steel-tired rollers only. Two 9-11 t steel-tired rollers shall be provided for each paver in use. Compaction shall be carried out immediately after the mixture is placed due to rapid cooling of the mixture.

Requirements for Completed Pavement Courses

Temporary Ramps

At the end of each completed portion, prior to opening of the lanes to traffic, the completed sections of the bituminous surfacing shall be ramped down to the existing pavement at a slope of 25 mm in 3 metres.

The material to be used for construction of the ramps shall be as determined on the site by the Engineer.

In all cases, the transition shall not form part of the permanent pavement, but shall be removed before the paving of the adjacent section.

Measurement for Payment

The payment quantities indicated on the tender are based on mixes consisting of steel slag aggregates only. The quantity of payment for traprock and

gravel O.F.C. mix incorporated into the work shall be determined by multiplying the total measured mass of O.F.C. mix with the appropriate factor given in the table below:

Origin of Raw Material for Aggregates	Multiplying Factor
Steel Slag	1.000
Quarried Trap Rock	1.109
Gravel	1.203

DESIGNER'S NOTES: * Use Option A when the Authority supplies asphalt cement.

** Indicate penetration grade of asphalt cement.

WARRANT: Always with this tender item.

Slag improves pavement's skid resistance

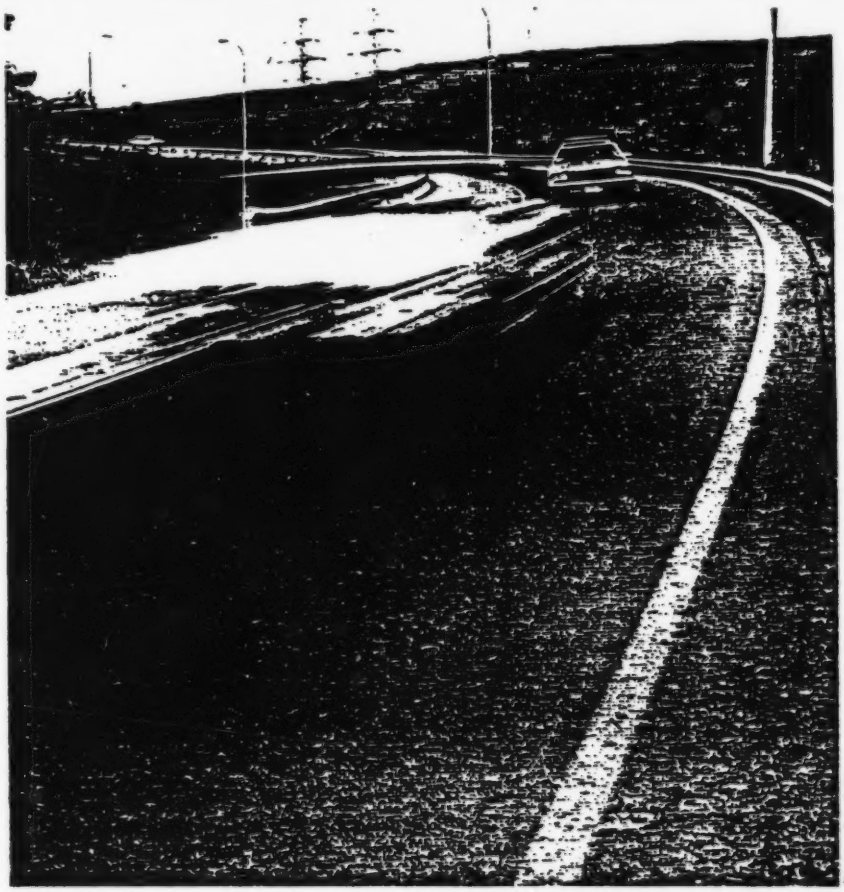
Slag, a byproduct of the steelmaking process, is an excellent paving material for highways and roads with high traffic speeds and volumes. Slag has a rough surface texture similar to that of sandpaper, so tires grip the pavement well, even on tight curves and in rainy weather. Contractors find steelmaking slag easy to work with and economical. Both coarse and fine slag pieces (see lower photograph) are mixed with asphalt cement to make this exceptionally skid-resistant pavement.

Tests by the Ontario Ministry of Transportation and Communications (MTC) show that slag, a byproduct of the steelmaking process, is one of the best aggregates for making skid-resistant pavement.

Eighteen bituminous test sections were constructed on critical areas of Highway 401, Toronto. The tests involved various mixes of fine and coarse steelmaking slag, blast furnace slag, and traprock as well as limestone screenings and sand, with an asphalt cement binder. The Ministry test report notes: "Blast furnace slag and steel slag aggregates appear somewhat better than the traprock aggregate used widely in the past for main highways in Ontario."

Slag is an excellent paving material because it retains its good macrotexture and microtexture. A bituminous mix containing slag has a rough surface, or macrotexture. It's permeable, so water drains through the surface course. Its ragged microtexture inhibits water film formation. Each particle has a texture similar to sandpaper so tires grip the pavement effectively, helping to prevent aqua-planing. And, since steelmaking slag particles are extremely hard and coarse throughout, they don't smooth out even after years of heavy service. Slag also imparts high stability to pavement which inhibits rut formation.

For these reasons, slag fulfills MTC paving material specifications for roads with high traffic speeds and volumes. Now paving contractors are using it more and more for major highways and in municipalities for busy roads and bus stop areas. Many contractors find slag economical; like other aggregates, its price is influenced by the distance from the source to the job site. Contractors also find slag easy to work with; its high heat retention means less energy is needed to heat the paving mix and its high density means less rolling compaction is necessary.



Photos Tim Fuglo

Slag contains the nonmetallic substances removed from molten steel during production. Previously, slag was used as landfill. Today, its use as a paving material solves two environmental problems. Stelco doesn't have to search for new sites to dispose of the material; all of it is sold through Steetley Industries in Dundas, Ontario. And, since slag is being produced anyway, there is no need to quarry environmentally sensitive areas. Tom Kovich, Head of Soils and Aggregates at the MTC, comments: "We don't refer to steelmaking slag as a waste product anymore because it's so well utilized." Andrea Murphy

DOFASCO ILLUSTRATED NEWS, Vol. 49, Issue No. 5/85

Paving the way

By Kim Bryson / Photography by Al Tone

High above the narrow sand spit that shelters Burlington Bay from Lake Ontario, thousands of automobiles travel each day to destinations unknown. Most drivers are fully aware that, like the old Skyway Bridge, they are manoeuvring atop a giant tapestry of concrete and structural steel. But steel goes much further than the eye can detect. Even the slim slivers of fresh asphalt that cover the new Burlington Bay James N. Allan Skyway Bridge have come within the scope of steelmakers. Steel slag asphalt was the icing on the cake as the new Skyway Bridge opened for travel in October 1985. Most fitting for Canada's "Steel City", the development of this product has become a cooperative, local, success story.

The Hamilton-based Red-D-Mix Concrete Company, in conjunction with Dofasco, developed not only a popular and widely used asphalt mix, but also an efficient and economical method for recycling a steelmaking by-product. Slag is a composite material that has hitherto been limited primarily to iron recovery and recycling to the blast furnaces at Dofasco and landfill applications. But as of 1979, the two companies moved jointly into a market just beginning to search for new and superior alternatives.

"Our goal here at Dofasco is to reduce all the by-products in the steelmaking process," says Al Ott, Supervisor, By-Products Distribution. "For those we cannot reduce further, we seek new internal uses or other applications in other industries."

In an age when environmental concerns are receiving top priority, recycling of by-products is highly important.

According to Al, "Ten or fifteen years ago build-up of this by-product represented a potential problem to Dofasco. Now it is in demand for the production of a product that touches upon and improves our quality of life."

John Wilson, Purchasing Department Manager, By-Products Distribution, adds, "We have worked closely on this with our Environmental Control Group here at Dofasco and with the Ministry of the Environment." Since the inception of the project, Dofasco has more than doubled its sale of slag to the Red-D-Mix Concrete Company for use in Steel Slag Asphalt while approaching the goal of 100 percent recycling of steelmaking slag.

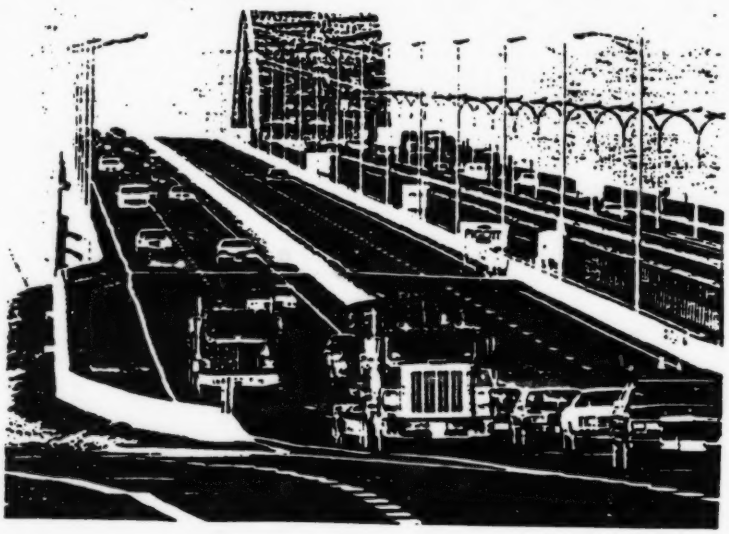
Steel slag asphalt has been Earl Kee's most important project over almost two decades. As Manager of Red-D-Mix's Asphalt Division, he has "been behind this from the word go." Years of research, tests and collection of data, in conjunction with Bob Cotsworth, National Slag, and Dr. John Emery, Trow Associates, has finally paid off with the success of this road surfacing material.

"This all took time," reflects Earl, "it was seven or eight years before we could accumulate the data to go to the Ministry of Transportation and Communications." And go they did. In the words of Ministry spokesman Dan Lynch: "At this point in time steel slag has virtually all of the market with a total volume of between 150,000 and 250,000 tonnes per year." What this figure tells us is that at some time, be it a parking lot or more likely a heavily-travelled highway, we drive on asphalt surfaces made of steel slag.

Slag for use in asphalt is an aggregate composed of pieces screened to under one half inch in length or width (larger pieces are recycled at Dofasco for use, in the blast furnaces). Red-D-Mix blends these sized steel slag pieces with liquid asphalt to produce a premium mix which eventually results in a surface that costs a little more than conventional asphalt; however, steel slag is rated as superior in terms of strength, flexibility and wearability. For drivers, that adds up to increased safety on the road.

Factors leading to the present popularity of steel slag asphalt include a combination of its own qualities and dwindling supplies of naturally-occuring traprock, an ingredient in other asphalt alternatives. In the Hamilton area where the first and most extensive use of steel slag has been made, the future looks bright. According to George Stone of the Hamilton-Wentworth Region, satisfaction with the product is at an all-time high. "We are quite happy with steel slag and the main reasons center around its high skid resistance and durability."

For Earl Kee and Red-D-Mix, success speaks for itself. For Dofasco, not only has a new product been developed but an old problem has been remedied. Perhaps the best summation was that of Al Ott when noting: "Using our steelmaking slag by-product as an aggregate for asphaltic mixes, we have a practical replacement for traprock which is a non-renewable natural resource."



ANOTHER

SLAG SUCCESS STORY

THE ALL-PURPOSE CONSTRUCTION AGGREGATE

STEEL SLAG BITUMINOUS MIXES PROVIDE LONG LIFE AND HIGH SKID RESISTANCE

Steel slag has been used extensively in bituminous mixes for more than 10 years on major highways and interstates with high ADT's and heavy truck traffic. These pavements have maintained high skid resistance and have remained in excellent physical condition, demonstrating under actual traffic that steel slag bituminous concrete provides safe cost-effective highway surfaces.

Steel slag mixes have the following special characteristics: high stability (in excess of 3000 Marshall stability by ASTM D 1559); high skid resistance; lower drying costs due to its low absorption; longer heat retention after mixing, and ease of campaction without "shoving" in front of roller.

Documentation of the excellence of steel slag mixes is provided by field tests conducted by the Ontario (Canada) Ministry of Transportation and Communications on the Toronto By-Pass portion of the high speed limited access Highway 401 over a period of 4 years. 3 year test data have been published in IR-67 Skid Resistance of Bituminous Pavement Test Sections, Highway 401, Toronto By-Pass, Ontario Ministry of Transportation and Communications, April 1978, and 4 year test data were published in Transportation Research Record 712 of the Transportation Research Board.

In these tests steel slag mixes retained higher SN's at 60 m.p.h. than trap rock as shown in table 1. Sedimentary coarse aggregates were not included in the test series since earlier tests on a similar type test section on highway 400 had indicated relatively low skid resistance. Mix data is provided in table 2.

Table 1

Test Sec. #	% Coarse-Fine	Driving Lane ADT 12,000 Initial	Driving Lane ADT 12,000 4 yrs.	Center Lane ADT 17,300 Initial	Center Lane ADT 17,300 4 yrs.	Passing Lane ADT 14,600 Initial	Passing Lane ADT 14,600 4 yrs.
7	45SL-55SLS	48	33	46	31	49	35
3	45TR-55TRS	45	27	47	28	47	33

TR Traprock. TRS Trap screenings. SL Steel Slag, SLS Steel Slag screenings.

Table 2

Aggregate	% Ret #4 by wt.	Asphalt % Wt. of Mix	Marshall Stability lbs.	Marshall Flow 0.01 in.	V.M.A. % Vol.	Voids % Vol.	*
All Trap	47.5	4.1	3185	16.5	12.9	1.2	L
		4.0	3407	15.3	13.5	2.0	F
All Steel	46.8	5.3	3520	16.0	18.5	2.7	L
slag		5.2	3640	13.2	18.7	3.3	F

*L - Laboratory mix design F - Field laboratory tests

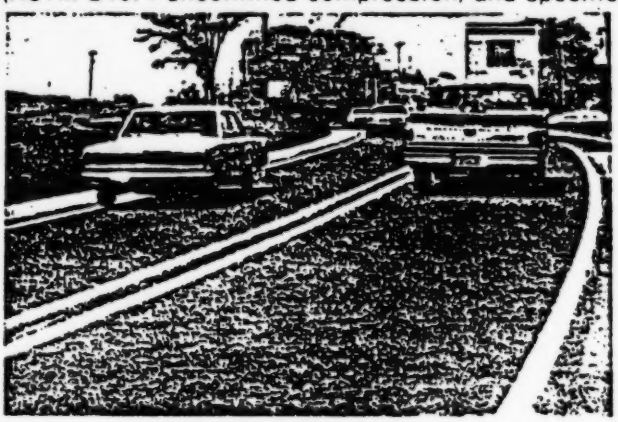
In 1979 and 1980, the Indiana Toll Road resurfaced 92 miles of 4 lane pavement using the same "all steel slag bituminous mix" as the Province of Ontario. Also during this same period the state of Indiana resurfaced interstate and U.S. routes, totaling 36 miles, using steel slag bituminous mixes. Added to this list of users are the counties of Elkhart, LaPorte and Porter; and the cities of South Bend, Mishawaka, Portage, Elkhart and Valparaiso. Among other states with excellent skid resistant performance and durability are: Illinois, Missouri, Minnesota, California and Alabama.

In the St. Louis, Missouri, area steel slag mixes have provided high skid resistance and durability since placement in 1973. One of these was a steel slag bituminous dense graded surface course on heavily traveled Route 115 near St. Louis which has maintained high friction numbers after 7 years of traffic. The friction number shortly after placement was 56; tests made in 1979 showed the SN's to be 51 and higher.

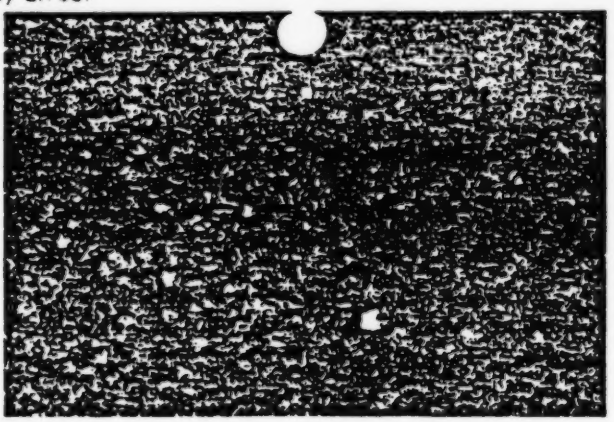
The individual aggregate gradations and mixture proportions were as follows:

	Size Distribution Each Aggregate				Size Distribution Total Mix				
	1/2" slag	3/8" slag	Natural sand	Limestone filler	slag 1/2"	3/8" slag	sand	filler	Mixture Composition % by Weight
1/2-3/8	4.8				1.9				1.9
3/8-4	70.2	2.7			27.9	1.1			29.0
4-10	20.4	46.6			8.1	18.6			26.7
10-40	0.6	37.4	1.8		0.2	15.0	0.2		15.4
40-80	0.5	4.8	32.5	1.8	0.2	1.9	3.6	0.1	5.8
80-200	1.4	3.2	63.3	14.6	0.6	1.3	6.9	0.6	9.4
-200	2.1	5.3	2.4	83.6	0.8	2.1	0.3	3.3	6.5
	100.0	100.0	100.0	100.0	39.7	40.0	11.0	4.0	94.7
								Asphalt	5.3
								Total	100.0

5.3% 60-70 penetration AC bitumen was used. The lab mix characteristics were: voids 5.19%, stability 469 (ASTM D1074-unconfined compression) and specific gravity 2.793.



General view of surface after 7 years of traffic



Closeup of texture after 7 years of traffic

Steel slag mixes have been in use in the Detroit, Michigan area since 1959. The City of Detroit has 60 miles of streets which were placed in 1961 to 1963 that have had virtually no maintenance for repair or resurfacing. After 17 plus years these streets are still in excellent condition. In 1978 the Province of Ontario started a bituminous resurfacing program of Highway 401 near Windsor using steel slag aggregates in the surface course. Approximately 30 miles of 4 lane pavement were placed in 1978-1979 with excellent results in skid numbers.

Excellent stability, long life and high skid resistance are the advantages received when steel slag is used in bituminous pavement mixes.

NATIONAL SLAG ASSOCIATION
300 South Washington Street
Alexandria, Virginia 22314
(703) 549-3111

ANOTHER

SLAG SUCCESS STORY

THE ALL-PURPOSE CONSTRUCTION AGGREGATE

STEEL SLAG REQUIRED ON THE ILLINOIS STATE TOLL HIGHWAY

During the period 1981 through 1984, eighty-five thousand (85,000) tons of steel-slag coarse aggregate were used by five separate contractors for the surface course on all ramps and approaches, bridge approaches, and super-elevated horizontal curves on the 256-mile Tri-State Tollway.

Steel slag was required by the specifications, as it was the only aggregate that will meet the requirements of their 10-year wet skid-resistance program.

FINISHED TOLLWAY

The steel-slag coarse aggregate was required to meet the following grading requirement:

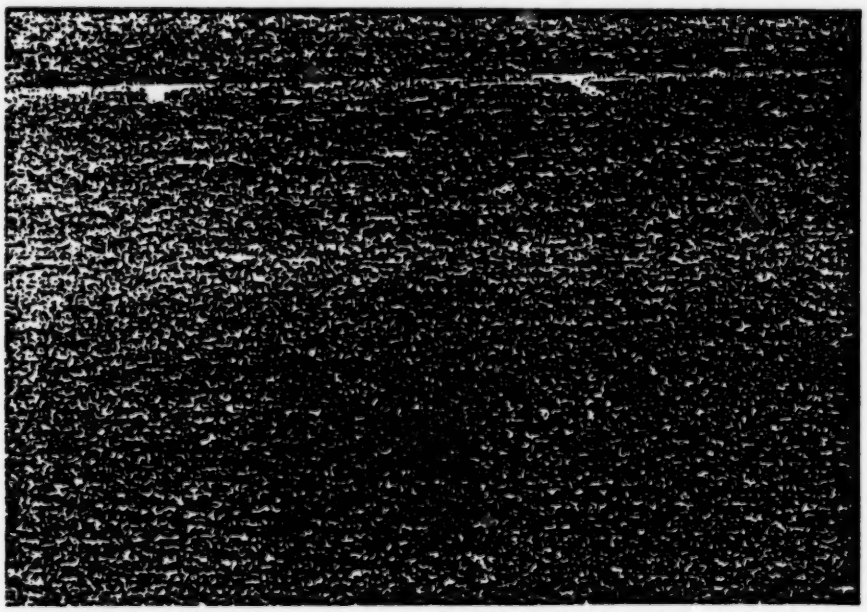
Sieve Size	% Passing	Sieve Size	% Passing
¾	100	No. 4	20-50
½	94-100	No. 16	0-14
⅜	70-90	No. 200	0-6

The following open-graded combined grading, consisting of 68% coarse aggregate and 32% fine aggregate, was specified in order to enhance self-drainage:

Sieve Size	% Passing	Sieve Size	% Passing
¾	100	No. 16	22-33
½	95-100	No. 30	17-27
⅜	77-92	No. 50	12-21
No. 4	33-61	No. 100	7-15
No. 8	28-47	No. 200	2-9

The mix design provided for an air-void content of 3.19 with 78.5% of the aggregate voids being filled with bitumen. The specification required Marshall stability to be in excess of 2500; the mix used had stability in excess of 3100.

Payment for the bituminous concrete surface course (modified) was on a per-ton basis.



CLOSE-UP OF TEXTURE

IMSASLAG® TYPE-S

Steel slag and asphalt

Steel slag has a strong affinity for asphalt in all types of pavement applications.

Angularity, low absorption, high heat retention, blackness, hardness—all combine to impart the following characteristics:

1. High, long-term skid resistance. (Typical numbers-SN-: 56 at 235,000 passes; 51 at 1,500,000.)
2. Permanent blackness, allowing painted pavement markers to show up longer.
3. Economic use of liquid asphalt (typical hot mix overlay calls for between 4.9 to 5.5%).
4. Longer transportation and working periods and lower mixing temperatures due to high heat retention.
5. Extremely high stability. (ASTM D-1074536 versus 447 for traprock, for instance. Marshall stability—excess of 3500.) Very good rut-resistance.
6. Good flow characteristics for easy placement and compaction.
7. Does not strip.
8. High resilient moduli (M_R) values allowing design of sections thinner than necessary with most natural aggregate mixes.

Steel slag has been used successfully in:

- Hot mix surface courses
- Chip seal
- Slurry seal
- Seal-coating
- Cold mix patches and shoulders

IMS

INTERNATIONAL MILL SERVICE, INC.

1818 MARKET ST., PHILADELPHIA, PA 19103, PHONE: (215) 963-2600

10-85

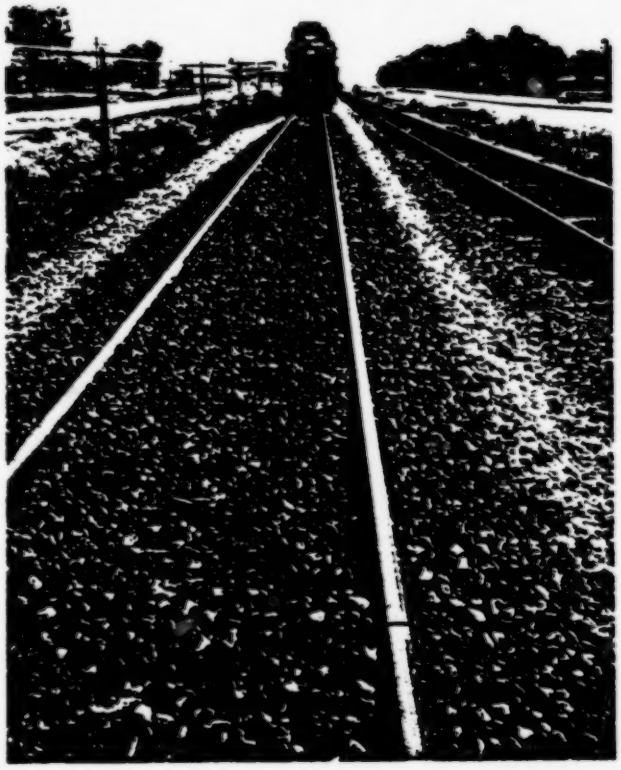
IMSASLAG® TYPE-S

Steel slag railroad ballast

Steel slag ballast has all the characteristics desirable in mainline ballast, field-proven over the past several years by many of the nation's leading railroads.

They are:

- Heavyweight—providing high resistance to lateral thrust on curves and protection against washout in areas subject to flooding.
- High percentage of void space—providing consistently good drainage.
- High resistance to abrasion—minimizing degradation and loss of elasticity in the section itself.
- Cubical fracture and extreme angularity—combined with heavyweight, assure total interlock and resulting very high stability under all track conditions.
- High electrical resistance—assuring no interference with electrical rail signal systems.
- High resistance to chemical attack—freeze-thaw, wet-dry degradation influences.



Physical Properties:

Property	Steel Slag	AREA Specifications
Weight per cubic foot	125 lb. (avg.)	100 lb. min.
Clay Lumps	None	0.5% max.
Soft and Friable Pieces	Negligible	5.0% max.
Material Finer than 200 Sieve	Less than 0.5%	1.0% max.
Los Angeles Abrasion Loss	Less than 30%	40% max.
Sodium Sulfate Soundness Loss	Less than 5%	10% max. (5 cycles)
Electrical Resistance	More than 15.0 ohms	2.0 ohms min. per 1000 lineal ft. of track (AAR)

Processed steel furnace slag also meets all other AREA specifications and AAR recommendations as indicated in this tabulation.

INTERNATIONAL MILL SERVICE, INC.
1818 MARKET ST., PHILADELPHIA, PA 19103, PHONE: (215) 963-2600

IMSASLAG® TYPE-S

Chip sealing with steel slag

Steel slag chips are highly preferred in this application for the following reasons:

- High, long-term skid resistance.
- Permanent blackness.
- Very little loose excess.
- Quickly achieved stability

Steel slag chips are:

Hard	6.5 to 7 on Moh's Scale.
Tough	L.A. Abrasion Loss—17 to 30%
Freeze-thaw resistant	Sodium Sulphate Soundness Loss under 5%.
Compatible	with entire range of asphalt types, including emulsions.

Irregularly cubical steel slag chips will not polish.

Estimating data for typical application:

Liquid Asphalt	.25 to .30 gallons per square yard.
Chips	23 to 28 pounds per square yard.

(Range given takes into account differing surface conditions such as flushing or dried out).

INTERNATIONAL MILL SERVICE, INC.
1818 MARKET ST., PHILADELPHIA, PA 19103, PHONE: (215) 963-2600

10-85

IMSLAG® TYPE-S

Stabilize and surface with steel slag fines

Steel slag is a uniquely stable, cementitious aggregate widely used in the construction and maintenance of:

- Truck and equipment yards.
- Railroad and utility service roads.
- Parking lots.
- Alleys.
- Product storage areas.
- Cattle feed pens.
- Road shoulders and gutters.

Steel slag fines when placed, wetted and rolled actually harden in place. They produce a tough, long-wearing platform capable of withstanding heavy point loads (such as trailer jacks) and severe scrubbing action (fork lifts, dual drivers).

In some instances, road maintenance agencies have finished off wetted and compacted slag with a shot of emulsion—thereby creating a shoulder, for instance, barely distinguishable from asphaltic concrete.

Most effective performance is obtained by wetting steel slag fines *before* final placing to avoid segregation of fine and coarse particles. Wetting should be thorough to the point of apparent sloppiness. Compaction is achieved quite easily. In many cases a few passes with the water truck, end-loader or motor-grader tires is enough. Minimum thickness for effective hydration . . . 4 inches

IMS

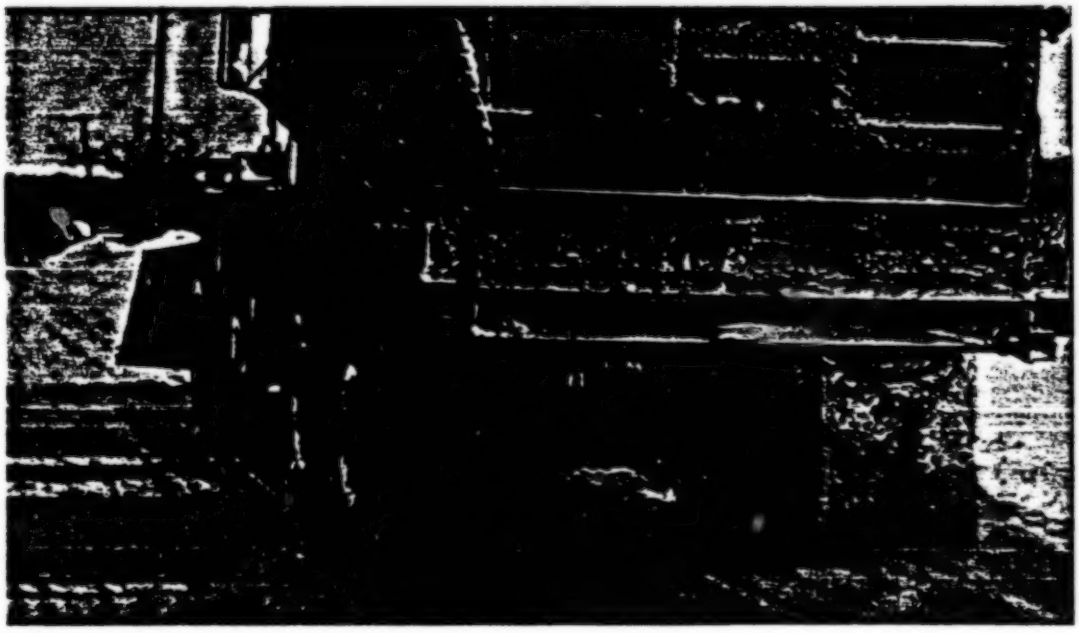
INTERNATIONAL MILL SERVICE, INC.

1616 MARKET ST., PHILADELPHIA, PA 19103, PHONE: (215) 963-2600

10-85

IMSASLAG® TYPE-S

Imsaskid steel slag fines for ice-control



- Dark color, almost black, absorbs sun's heat and embeds in ice.
- Angular particles provide skid-resistant tire-grip.
- Heavy weight keeps IMSASKID from blowing out of traffic lanes, even in high winds.
- High lime content hastens ice-melt and inhibits freezing in stock-piles.
- Chemically inert, non-corrosive, will not damage vehicles or planted road shoulders.
- Quality-controlled; graded to meet applicable Highway Department specifications.

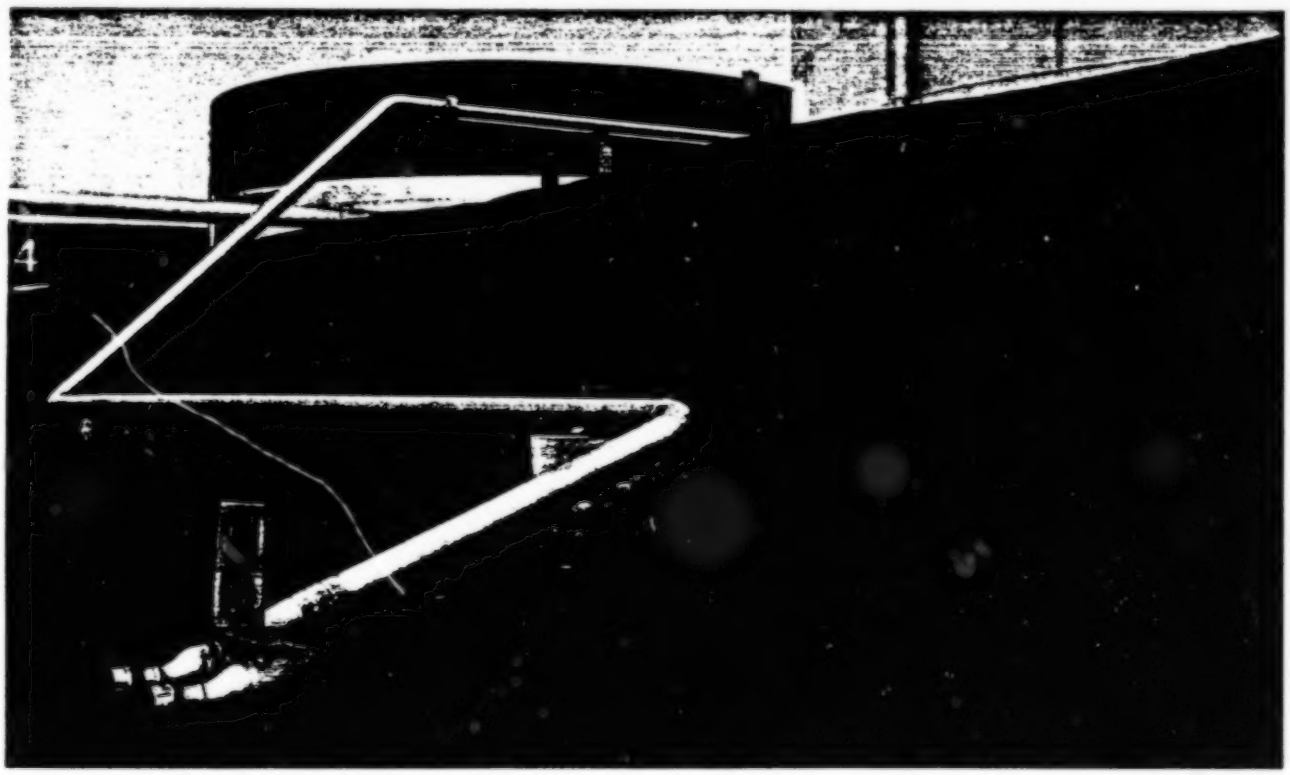
IMS

INTERNATIONAL MILL SERVICE, INC.

1818 MARKET ST., PHILADELPHIA, PA 19103, PHONE: (215) 963-2600

imsawall®

The Maintenance-Free Fire Wall and Retention Barrier Material



Made from steel furnace slag, IMSAWALL is a highly effective material for use in the construction and maintenance of fire walls and retention barriers for oil refinery and chemical storage tanks.

The angularity of the slag particles interlock, eliminating washouts and retarding vegetation growth. Its high angle of repose enables easy placement on dike walls.

Hundreds of thousands of tons of IMSAWALL have been used successfully by the petroleum and chemical industries throughout the United States.

For further information:

INTERNATIONAL MILL SERVICE
Aggregate Sales Department, 1818 Market Street, Philadelphia, PA 19103

COMPARISON OF CHEMICAL AND PHYSICAL PROPERTIES
THREE TYPES OF STEEL SLAG

	Average			Range		
	Electric	BOP/QBOP	Mixed Elec/BOP	Electric	BOP/QBOP	Mixed Elec/BOP
SiO_2	16.9	14.1	18.6	10.9-20.3	11.1-16.8	10.1-33.41
Al_2O_3	8.1	1.9	5.9	1.4-11.4	1.0-6.4	2.8-7.58
CaO	41.2	44.4	33.6	25.6-49.1	35.9-49.4	28.6-41.5
MgO	10.2	7.4	9.3	6.6-11.9	5.2-8.6	6.2-13.51
MnO	3.6	5.7	no data received	(only 1 report) 3.6	4.0-6.6	no data received
S	0.23	0.17	1.00	.014-.276	.04-.68	.10-1.55
FeO	18.1	22.4	no data received	4.0-25.6	17.0-25.9	no data received
Fe	13.6	20.7	15.6	4.2-36.4	15.5-24.2	3.1-24.5
P_2O_5	0.63	0.75	no data received	.30-.88	.57-1.14	no data received
P	0.43	0.28	0.39	.024-2.16	.21-.35	(only 1 report) .39
Wt[1] lb/ft^3	105.8	126	112.5	101.4-113.8	110-140.7	111.6-113.4
ABS	2.5	2.42	1.2	(only 1 report) 2.5	1.0-3.7	(only 1 report) 1.2
Sp. Gr.	3.3	3.3	3.27	(only 1 report) 3.3	3.21-3.37	(only 1 report) 3.27
LA[2]	20.4	15.6	17.2	18-22.9	8.9-29.0	(only 1 report) 17.2

(1)Grading, cooling and test methods not specified

RECOMMENDED PROCEDURE

Determination of Free Calcium Oxide in Steel Slag by Ethylene Glycol Extraction

The determination of free calcium oxide (free lime) is based on soluble calcium glycolate formed by ethylene glycol and free lime without influencing the combined lime in silicates, aluminates, etc. The method has been adopted from the cement industry.

To get a proper result the sample has to be ground very finely. The ethylene glycol used must be anhydrous, neutral and clear to suppress reaction with the combined lime. Furthermore, it must be very pure and should not be regenerated more than twice. All equipment used for the determination has to be absolutely dry.

Procedure:

1. Weigh out one gram of finely ground steel slag (minus 75 μm) and transfer to a 200 ml flask together with a pinch of dry standard sand (C109 Ottawa sand).

2. Add 30 ml ethylene glycol and 15 ml absolute methyl alcohol.

3. Bring the sample into suspension by shaking and then place the flask in a water bath and boil for 30 minutes under a reflux condenser, with occasional shaking.

4. Filter the contents of the flask through a suction filter, using a SS-White filter paper. Wash the flask twice with 10 ml alcohol and finally wash the filter once with 10 ml alcohol.

5. Add 10 drops bromo-thymol blue indicator and titrate with 0.1 N HCl until yellow-green.

Result:

ml of HCl used x 0.28 = % free CaO.

Proposed changes to PennDOT Form 408 as follows:

703.3(a)

3. Slag. Type A or C aggregate shall be crushed and prepared from tough, hard, durable pieces of air cooled blast furnace slag. The slag shall be obtained as a by-product in the production of pig iron and shall be reasonably uniform in density and quality.

Type C aggregate may be crushed and prepared from tough, hard, durable pieces of steel slag and shall be reasonably uniform in density and quality. After gradation preparation, steel slag coarse aggregate, whether re-claimed from an old stockpile or processed directly from the steel making process, shall be placed in a controlled stockpile initially in a fully saturated condition. The method of constructing and controlling the stockpile during the cure period shall be submitted to the engineer for his review. The slag shall then be kept in a reasonably uniform moist condition in the stockpile for a period of not less than 6 months in which the average monthly temperature is above 40^{0}F. After this minimum cure period, the stockpile shall be sampled by the engineer and the slag shall be tested by the BMTR for expansive characteristics in accordance with PTM 130. The steel slag stockpile will only be approved for use if the average volumetric expansion by PTM 130 is less than 0.50 percent. If the stockpile does not pass this expansion criterion for its use, it shall not be re-sampled and re-tested until a minimum additional cure period of 2 months from the time of the last sampling has elapsed. Steel slag aggregate may only be approved for use in the construction of modified subbase, subbase, selected material surfacing or stablized shoulders. Approved steel slag may be blended with other approved aggregates to uniformly and consistently maintain the grading required for the specified item of construction.

Bureau of Materials, Testing & Research

METHOD OF TEST FOR EVALUATION OF POTENTIAL EXPANSION OF STEEL SLAGS

1. Scope

1.1 This method of test covers the determination of the rate of expansion of steel slags where compacted and tested in the laboratory. Steel slags, produced in steelmaking processes such as open hearth, basic oxygen and electric arc furnaces, are generally expansive with volume changes of up to 10% attributable to the hydration of calcium and magnesium oxides.

1.2 This method is also applicable to any particulate material suspect of having expansive characteristics.

2. Apparatus

2.1 Mold - The mold (see Fig. 1) shall be of metal, cylindrical in shape, with an inside diameter of 6 ± 0.005 in., (15.24 cm ± 0.13 mm) and a height of 7 ± 0.005 in. (17.78 cm ± 0.13 mm). It shall be provided with a metal extension collar 2.0 in. (5.08 cm) in height, and a perforated metal base plate 3/8 in. (9.53 mm) in height. The perforations in the base plate shall not exceed 1/16 in. (1.59 mm) in diameter. The mold apparatus should be well coated with a rust preventative or constructed of stainless steel.

2.2 Spacer Disk - A circular metal spacer disk (see Fig. 1) 5-15/16 in. (15.08 cm) in diameter and 2.416 (6.14 cm) in height.

2.3 Rammer - A metal rammer as specified in Section 2.2, PTM 106.

2.4 Expansion-Measuring Apparatus - An adjustable metal stem and perforated plate, with perforations in the plate not exceeding 1/16 in. (1.59 cm) in diameter, and a metal tripod to support the dial gage for measuring the amount vertical expansion (see Fig. 1).

2.5 Weights - Two annular metal weights or four slotted metal weights totalling 10 lbs (4.54 kg), 5 7/8 in. (14.92 cm) in diameter, with a center hole 2 1/8 in. (5.40 cm) in diameter (see Fig. 1).

2.6 Gage - Dial gage reading to 0.001 in. (0.025 mm).

2.7 Miscellaneous Apparatus - Other general apparatus such as a mixing bowl, straightedge, scale, submersion tank or bucket, filter paper, dishes, and 160 ± 5 F (71 ± 3 C)

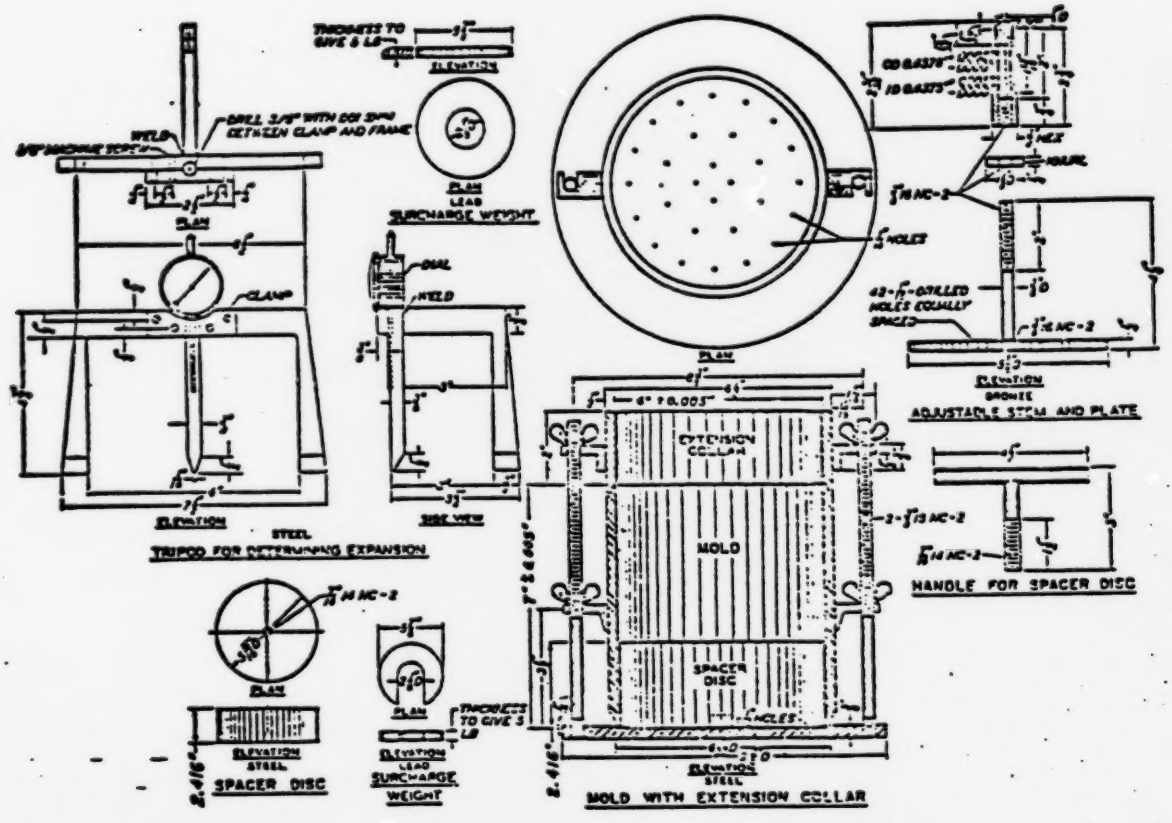


Fig. 1 - Expansion Test Apparatus

3. Stockpile Sampling

3.1 Three representative samples, two sample bags or approximately 100 pounds of material per sample, shall be obtained from each stockpile or sublot. One sample shall be obtained at a random location from each of three separate faces of the stockpile.

3.2 Since aggregate segregation usually occurs when the material is stockpiled, with the coarser particles rolling to the outside base of the pile, it is necessary to excavate into the base of the stockpile with power equipment to obtain a representative sample. At least two scoop loads of the representative material shall be thoroughly mixed on a separate pile by the power equipment and then "backbladed" to form a level surface. The sample shall then be obtained by channeling in one direction across the middle of the level surface. If additional material is needed, another channel may be made at approximately right angles to the first near the middle of the level surface.

3.3 Identification

3.3.1 The following identification shall accompany each sample:

3.3.1.1 Sample number - each sampled stockpile will have three separate samples numbered 1, 2 and 3,

3.3.1.2 Name of owner or seller,

3.3.1.3 Stockpile identification or designation,

3.3.1.4 Date the stockpile was sealed to start the cure period,

3.3.1.5 Approximate quantity available in the stockpile.

4. Sample Preparation for Density

4.1 Prepare the sample in accordance with PTM 106, Section 4 (Method B).

4.2 Select and maintain separate representative samples of slag passing the No. 4 sieve and the 3/4 in. sieve but retained on the No. 4 so that the total sample will weigh approximately 14 lb. (6.36 kg.) or more for the moisture-density relationship and 12 lb. (5.44 kg.) or more for the molding of the test specimen. Set aside the portion of the sample to be used in the expansion test and store so as to minimize loss of natural moisture. The percentage, by oven-dry weight, of aggregate passing the 3/4 in. sieve and retained on the No. 4 sieve shall be the same as the total percentage larger than the No. 4 sieve in the original sample when the material is recombined at the time the moisture-density curve is made.

4.3 Determine the optimum moisture content and maximum dry density in accordance with PTM 106, Section 5 except that the 6 in. diameter mold depicted in Fig. 1, with the spacer disc in place, is used and that the soil be compacted in 3 equal layers with 56 blows per layer. That portion of material passing the 3/4 in. sieve and retained on the No. 4 sieve is used in the surface-dry condition.

5. Preparation of Test Specimen for Expansion

5.1 Using the 12 lb. (5.44 kg.) or more portion of unprepared sample at approximately the natural stockpile moisture (undried)., compensate for the aggregate larger than 3/4 in. as in Section 4.2 except the weights of the plus No. 4 and minus No. 4 material used in the procedure shall be adjusted for their respective natural moisture.

5.2 Clamp the well lubricated mold (with extension collar attached) to the base plate. Insert the spacer disc over the base plate and place a disc of coarse filter paper on top of the spacer disc. Compact the slag-water mixture into the mold in accordance with Section 4.3 above except the amount of water added should be adjusted downward to compensate for the approximate natural moisture content. Compact the sample at maximum density and optimum moisture as determined in Section 4.3. If other densities and moisture contents are desired, they may be used if indicated in the report.

5.3 Remove the extension collar and carefully trim the compacted soil even with the top of the mold by means of a straightedge. Patch with smaller size material any holes that may have developed in the surface by the removal of coarse material. Remove the perforated base plate and spacer disc, weigh and record the weight of the mold and compacted slag. Place a disc of coarse filter

paper on the perforated base plate, invert the mold and compacted slag, and clamp the perforated base plate to the mold with the compacted slag in contact with the filter paper.

5.4 Place the adjustable stem and perforated plate on the compacted slag specimen in the mold and apply weights to produce a 10 lb. surcharge. Submerge the mold and weights in water, which has been preheated to 100 + F (38 + C), allowing free access of water to the top and bottom of the specimen.

5.5 Place the submerged sample in a level position in a controlled oven at 160 + 5F (71 + C).

5.6 Seat the tripod on the extension collar and adjust the dial gage to zero reading. The dial gage should be set so that its piston is not fully extended. This will allow for measurement of initial sample settlement or consolidation.

6. Procedure

6.1 Record an initial gage measurement taken 30 minutes after the sample was placed in the 160 ± 5 F (71 ± 3 C) oven. This measurement is the base reading and allows for thermal expansion of the test apparatus.

6.2 Dial measurements should be recorded a minimum of once daily (preferrably the same time each day) thereafter for a period of at least one week.

6.3 Sufficient water should be added each day so that the test specimen remains fully submerged and not within 2 hrs. of the time for dial measurement readings.

6.4 After a period of one week, the test specimen should be removed from the tank or bucket and replaced in the 160 ± 5F (71 ± C) oven in an unsubmerged but saturated condition for an additional one week period.

6.5 Dial measurements for the unsubmerged sample should be continued as in 6.2. Measurements should not be obtained within 2 hrs. of the time of addition of water to the specimen.

6.6 A minimum of 500 cc of water should be added to the top of the sample each day so that the test specimen remains fully saturated.

6.7 Carefully dismantle the test specimen after the two week expansion period, and visually inspect it for crystalline growth on slag particle surfaces.

7. Calculations

7.1 Percent Volumetric Expansion - Calculate the percent expansion by dividing the dial gage measurement minus the base gage measurement by the initial sample height of 4.584 in. (11.64 cm).

7.2 Rate of Expansion - The rate of expansion is the slope of the plot of time in days (x-axis) versus the percent expansion (y-axis) shown in Fig. 3. Those parts of the curve developed during submerged and unsubmerged conditions should be clearly indicated and separate rates of expansion should be calculated for each of the two parts.

7.3 Percent Total Volumetric Expansion - The dial gage measurement after fourteen days of combined submerged and unsubmerged conditions minus the base dial gage measurement divided by the initial sample height of 4.584 in. (11.64 cm).

8. Report

8.1 The report shall include the following:

8.1.1 Particle size distribution curve of the original sample as per Fig. 6, PTM 103.

8.1.2 Particle size distribution curve of the prepared sample before testing as per Fig. 6, PTM 103.

8.1.3 The optimum moisture content and maximum dry density of the slag specimens as per Section 4.3 herein.

8.1.4 The moisture content and dry density of the molded specimens used in the expansion tests.

8.1.5 The expansion curve as depicted in Fig. 3 to include the total percent volumetric (one dimensional) expansion after 14 days and rate(s) of expansion.

8.1.6 The average of the 3 total volumetric expansions for the 3 material samples representing each stockpile.

8.1.7 Determination of pH of sample leachate and x-ray diffraction of sample, if specified.

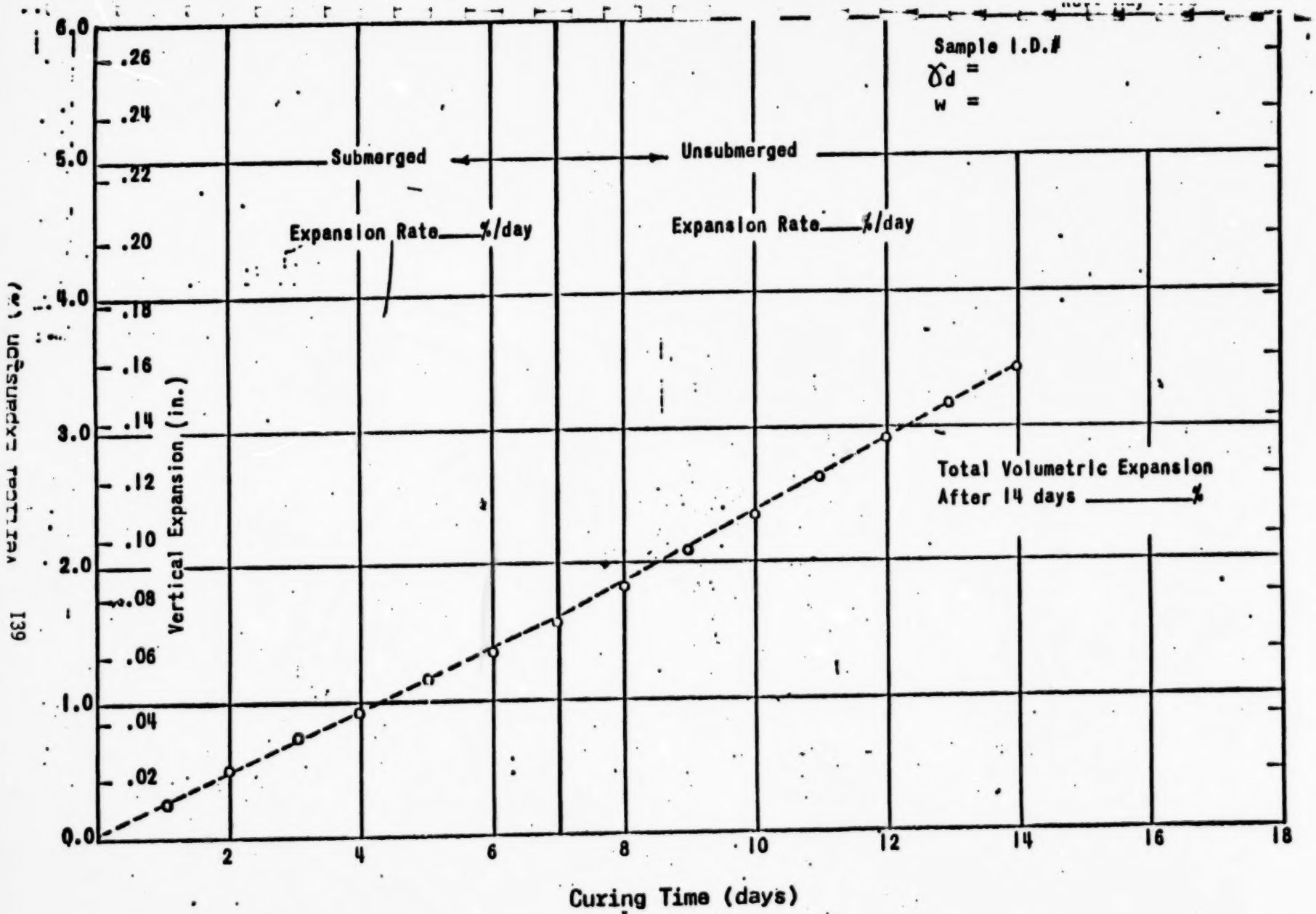


Fig. 3 - Typical Slag Expansion Curve